



OCEAN SOLUTIONS

EARTH SOLUTIONS

SECOND EDITION

Edited by
DAWN J. WRIGHT

Foreword by David G. Gallo

Afterword by Jerry R. Schubel

OCEAN SOLUTIONS EARTH SOLUTIONS SECOND EDITION

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Dedication

To Peter Kouwenhoven, lead author of chapter 5, who on July 24, 2015, passed away suddenly in his sleep while away in Japan on business. We continue to extend our deepest sympathies to Peter's family and to his colleagues at CLIMsystems in Hamilton, New Zealand. Peter will be sorely missed by GIS and climate change colleagues around the world.

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Foreword

We are living on an ocean planet. In fact, more than 70% of the earth's surface is covered by ocean water. The ocean is vast, deep, and in places represents some of the most remote, hostile, and dynamic environments on Earth. To date, we have explored less than 10% of the world beneath the sea, yet in our voyage of discovery, we find the most dramatic and dynamic topography on the planet; we find thriving ecosystems where we were sure there could be no life at all; and perhaps most important, we find keys and clues to the evolution of Earth itself. Although we are a long way from understanding the relationship between humanity and the sea, one important headline has emerged: a healthy global ocean is critical to human health. Any review of recent scientific literature, anecdotal evidence from those that live on or make their living on the sea, and environmental evidence all lead to one conclusion: the ocean is in deep trouble, and the world is facing a near-term crisis.

We used to think that the ocean was self-healing, too big to fail, and that there were no limits to its bounty. We now know those statements to be untrue. Over time, human activity has slowly but surely changed the chemistry and temperature of the sea. In addition, we have managed to collapse the stock of some of the world's greatest fisheries, and it's unclear how bad the situation really is. Through the growth of civilization, we are putting increasing environmental pressure on ocean ecosystems. No matter where on Earth we live, what we put on our fields, backyards, golf courses, and city streets eventually makes its way to the streams, rivers, estuaries, and the ocean; and in many cases, the results are catastrophic. Dead zones are becoming more widespread and long lived than ever. Today, more than 30% of the world's seven billion people live within the coastal zone, and 15 of the world's most populated cities are built either on the ocean or on estuaries. Population and coastal growth are continuing to rise, and along with that growth comes the risk from coastal storms, hurricanes, typhoons, and tsunamis. There is a desperate need to better manage our coastal zone.

If there is any good news, it is that *now we know*. We know that the ocean provides us with the greatest portion of the air we breathe, the food we eat, and the water we drink. We know that environmental pressure on the sea due to human activity is more, not less. We also know that regardless of where we live on planet Earth, we have an impact on the ocean. Conversely, regardless of where we live on Earth, the ocean has an impact on our everyday lives.

Despite knowing these important facts, there is a knowledge gap that must be filled. The ocean is complex, dynamic, and ever changing. It is clear that we need to create policy to better manage the ocean, but to be effective these policies must be based on fact as much as emotion. The ocean has a strong emotional pull, but if we are not careful in our actions, we will suffer from unintended consequences, and ultimately we will love this planet to death.

The past several decades have seen rapid growth in our ability to explore and understand the world beneath the sea. Observation is the cornerstone of science, and where the ocean is concerned, observation requires sophisticated technology. The development and deployment of new platforms (satellites, ships, submarines, remotely operated vehicles, autonomous undersea vehicles, towed systems, buoys, drifters, gliders, and more) and new sensors (sonars; cameras; physical, chemical,

and geophysical sensors) allow us to “see” the seafloor and waters above with unprecedented clarity, accuracy, and precision. This data, combined with airborne and satellite information, is for the first time providing an effective means of sampling the ocean at discrete locations as well as conducting long-term observations over entire ocean basins. All this data combined, complemented by new GIS analytical and modeling technologies and techniques, provides humanity with a new view of planet Earth. Consequently, it is becoming easier to recognize and observe the relationship between humanity and the sea. Herein lies the topic of this book.

To understand the ocean, we must understand what is “out there.” What are the components? How are they arranged? How do they change in time and space? The ability to recognize and observe relationships, patterns, and trends is the true gift of maps and the trilogy of GIS.

The ability to collect oceanographic data, especially multisensor/multiscale data, heralds the beginning of a new generation in ocean sciences. Combining these sensors and platforms with the ability to visualize and share information through GIS has led to an exponential growth of confidence in our ability to describe the ocean world. *So the publication of this book comes at a critical time. For the very first time, we can balance the term “ocean crisis” with the term “ocean solutions.” For the first time, we can share data and information with a global audience in a manner that allows them to participate.*

The challenge of understanding the relationship between humanity and the sea remains daunting. The goal of implementing policy to best ensure that the ocean is managed wisely is even more difficult. Nevertheless, these things are necessary and critical to a healthy ocean, a thriving planet, and human survival. We can perhaps draw from the wisdom that the longest journey begins with the first small steps forward. We now have the tools, and we can let the journey begin.

—David G. Gallo

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Dawn J. Wright
Esri Chief Scientist

Introduction

Dawn J. Wright

The ocean dominates the surface of the earth and greatly affects our daily lives. It regulates Earth's climate, plays a critical role in the hydrologic cycle, sustains a large portion of Earth's biodiversity, supplies food and mineral resources, constitutes an important medium of national defense, provides an inexpensive means of transportation, is the final destination of many waste products, is a major location of human recreation, and inspires our aesthetic nature. However, it also carries with it the threat of deadly tsunamis and hurricanes, industrial accidents, and outbreaks of waterborne pathogens. (National Academy of Sciences National Research Council 2011)

Our ability to measure change in the ocean is increasing, not only because of improved measuring devices and scientific techniques but also because new GIS technology aids us in better understanding this dynamic environment. The domain of GIS has progressed from applications that merely collect and display data to complex simulation and modeling and the development of new research methods and concepts.

GIS has traditionally provided effective technological solutions to the integration, visualization, and analysis of heterogeneous, georeferenced data *on land*. As early as the late 1980s, Esri began to make significant progress in the application of *ocean* GIS solutions to nautical charting, commercial shipping, oil spill response, and defense and intelligence. Recent years have seen GIS increasingly used in ocean science, conservation, and resource management communities, in large part because of the Esri Ocean GIS initiative launched in 2012 (Wright 2012). Many challenges remain, especially regarding inconsistencies in ocean data models, formats, standards, tools, services, and terminology.

Toward addressing these challenges, Esri held a one-time-only Oceans Summit at its headquarters in Redlands, California, in November 2012 (Wright 2013). Intermediate to advanced ocean GIS analysts and developers attended this invitation-only, high-level strategic workshop. Their goal was to help Esri move forward in its approaches to ocean-centric software, associated data formats, tools, workflows, and computing platforms. The success of that summit led to the annual Esri Ocean GIS Forum, open to all and first held in November 2013 (Pratt 2013). Presentations at the forum cover a wide range of topics, including ocean exploration and science, coastal management and marine spatial planning, coastal resilience and conservation, hydrographic surveying, commercial ship tracking, and closing technological gaps in multidimensional data handling and analysis.

Attendees have lauded these earnest efforts to apply GIS to the ocean (the open ocean as well as on or near the coast) and to resolve a range of technological gaps. Going forward, they also understand that the health and sustainability of the planet still lies in the balance. With water covering 71% of the planet's surface, it is clear that the ocean is critical to our lives, our energy, and our economy. This vital role is increasingly evident in the latest warnings from the UN

Intergovernmental Panel on Climate Change (2013), the Third US National Climate Assessment (Melillo et al. 2014), the launch of the US White House Climate Data Initiative, various calls to action from the academic community (e.g., Liu et al. 2015; Lubchenco and Grorud-Colvert 2015), and the search for Malaysia Airlines Flight MH370 (Smith and Marks 2014; still ongoing at the time of this writing). Not surprisingly, the nongovernmental organization (NGO) sector has also recognized the need for action. The Clinton Foundation's Blue Guardians, the XPRIZE Foundation (and its awarding of the Wendy Schmidt Ocean Health XPRIZE) (XPRIZE Foundation 2015), the Ocean Health Index initiative (Halpern et al. 2012; Halpern, Frazier, et al. 2015; Halpern, Longo, et al. 2015), the Mission Blue Sylvia Earle Alliance, the World Ocean Council, and the Schmidt Ocean Institute are just a few of the global-scale efforts emerging in recent years to focus on ocean sustainability.

Human-caused pressures have put the ocean in a state of deep crisis. *And if the ocean is in crisis, the Earth is in crisis.* At this pivotal juncture in history, we need good, digestible science to underpin solutions for

- protecting the ocean and ensuring our safety,
- managing and mitigating conflict among multiple and simultaneous uses of the ocean,
- geodesigning the ocean, and
- discovering and exploring a part of our planet that remains less understood than the moon, Mars, and Venus.

Ocean Solutions, Earth Solutions is about use-inspired science and realistic solutions for the ocean and thus the earth. With chapters drawn from among the best science presented at the 2013 Esri Ocean GIS Forum (first edition) and 2014 Forum (second edition), this book seeks to put that science into the hands of government decision-makers and ocean/coastal science researchers, state and local coastal zone managers, and ocean/coastal GIS practitioners. It also seeks to preserve good scholarship, including the emerging scholarship of students working on theses and dissertations. The editor and a sizable cadre of experts conducted a standard academic peer review of all chapters. The book encourages GIS best practices. Toward this end, it features an extensive digital supplement, including datasets with accompanying digital object identifiers (DOIs, in keeping with data publication trends; e.g., The Royal Society 2012; Leadbetter et al. 2013; Parsons and Fox 2013), geoprocessing workflows, GIS tools packaged as desktop extensions or web services, mobile apps, Python scripts, and Esri Story Map apps. Digital content for this book, described under “Supplemental Resources” at the end of pertinent chapters, can be accessed by QR code or URL or in the book's online resources (esri.com/esripress-resources/ocean-solutions-2e).

The solutions developed in these chapters lend credence to the hope that we can fix the problems of the ocean before it is too late—to build what Knowlton (2014) and others have tagged as a new #OceanOptimism hashtag on Twitter. In a similar vein, the Mission Blue (2014) initiative of the Sylvia Earle Alliance has established “hope spots.” Indeed, the efforts of scientists, resource managers, coastal engineers, and local communities have shown many promising results around the world. As Knowlton urges, we need to trumpet and seed these solutions.

The chapters of *Ocean Solutions, Earth Solutions* are divided into four main themes:

1. Server/cloud GIS
2. Coastal and marine spatial planning
3. Analytical and mapping tools
4. Visualization

During the 1980s and 1990s, GIS architectures were largely file-oriented, with Esri datasets structured as coverages and later as shapefiles. In the late 1990s, geographic datasets were placed into relational databases to allow for multiuser access. The web has evolved more recently to embrace

a service model powered by on-premise servers and/or the cloud, extending the old desktop data models with layers and web maps that travel *with* the data.

Chapter 1 represents the critical role that **server/cloud GIS** now plays in fisheries oceanography, particularly as local desktop resources are less able to handle the huge streams of data from ocean observatories, the complexity of numerical models, and the massive output files that these models generate. The chapter describes the on-premise, server-based Ecosystems Fisheries Oceanography Coordinated Investigations (EcoFOCI) Data Access and Analysis Tool (EcoDAAT) and the cloud-based LarvaMap, both developed for data integration and particle modeling to support fisheries oceanography and fisheries management. And because server/cloud GIS has become so important to data discovery and collaborative geodesign as part of coastal and marine spatial planning, it segues to the next theme of **coastal and marine spatial planning**.

Chapter 2 focuses on best practices for decision support guided by the popular Marxan approach when used in concert with GIS to inform multiple-objective ocean conservation and spatial planning. Chapter 3 (updated in the second edition) describes coastal and marine spatial planning programs under way in Martin County, Florida, and provides specific exemplars for data consolidation and organization, a workable data model and geodatabase schema, and GIS applications for managing artificial reefs and beaches.

The next theme highlights chapters that present specific **analytic and mapping tools**. Chapter 4 introduces tools for use in conjunction with the Coastal and Marine Ecological Classification Standard (CMECS), the first consistent US national classification for mapping and integrating ecosystem observations. The NatureServe observation toolkit and the CMECS crosswalking tool of the National Oceanic and Atmospheric Administration (NOAA) are examples of effective solutions for standardizing the collection of data in the field and uploading, validating, aggregating, and integrating that data with existing archives. Chapter 5 provides important guidelines and a desktop solution for accessing, mapping, and interpreting the output of numerical models used to project the effects induced by changes in atmospheric greenhouse gases. It describes the methodology used to extract the relevant ocean variables and considers the consequences of decision-making based on climate change scenarios. Policy makers and resource managers alike need such insights to create and manage climate adaptation and mitigation plans. A method and an accompanying ArcGIS tool for calculating a pollutant exposure index (PEI) for the Southern California Bight are the subject of chapter 6, which provides Python scripts for geoprocessing the exposure data and producing georeferenced PEI rasters for use with other spatial data to examine relative pollution risk for any area of interest within the mapped region.

Chapter 7 emphasizes mapping tools, in this case a map viewer to facilitate the management and monitoring of the Archipelago de Cabrera National Park in the Balearic Islands of Spain. The chapter includes useful guidelines for designing an intuitive interface with the Adobe Flash Integrated Development Environment along with the ArcGIS Viewer for Flex and creating the Open Geospatial Consortium Web Map Service. Chapter 8 (updated in the second edition) describes design principles and development of both a web app and a mobile app for mapping marine mammal distributions, drawing in large part from data contributed by citizen scientists. Chapter 9 (updated in the second edition) discusses the benefits of providing multiple computer pathways within the powerful web tool of the West Coast Ocean Data Portal to better enable search and connection to the services and datasets published by members of this network. These pathways include Catalog Services for the Web, the Esri Geoportal representational state transfer (REST) application programming interface (API), the OpenSearch API, and the Apache Solr REST API.

Chapter 10 analyzes land-cover data from the East End Marine Park of Saint Croix, US Virgin Islands, applying a landscape development intensity index for adjacent watersheds along

with an analysis of benthic habitat data from both benthic habitat maps and in-water surveys. The resulting maps are a powerful tool for understanding the connections between actions on land and impacts at sea, specifically the impacts of land-based sources of pollution on benthic habitats and species composition on fringing coral reefs. Chapter 11 employs a suite of both desktop and ArcGIS Online mapping and spatial analysis tools to develop a collaborative proposal to the Pacific Fishery Management Council. The proposal, which represents nearly a year's worth of discussion and trust building among commercial fishermen, conservationists, and local government, is for the design of spatial modifications to the current Pacific Coast groundfish essential fish habitat (EFH) conservation areas. The development of a Story Map app, in particular, helped this process. Chapter 12 focuses on Story Map apps again as one of many tools that the Aquarium of the Pacific uses to engage the public in lifelong learning experiences. The chapter provides best-practice examples in employing these tools to create a rich and informal science education experience that inspires learners to take action to protect and conserve ocean resources.

Chapter 13 begins the next major theme on practical solutions for improved **visualization** of the ocean. It reviews principles for integrating GIS and landscape visualization software to produce immersive and interactive four-dimensional models of the ocean. Planners and scientists provide feedback in a case study that tests these approaches within a marine protected area. Chapter 14 describes advances in visualization methods based on the Worldwide Telescope virtual globe and applies these methods to the management and analysis of data from marine microbial ecology and physical transport processes in the ocean. The discussion has implications on how to more effectively analyze and understand new harvests of large, complex datasets in three- and four-dimensional software environments that combine virtual globes with web GIS. Chapter 15 presents a framework adopted by the State of Oregon for managing the visual landscape of the territorial sea. The framework is part of the state's effort to plan for marine renewable energy development. We could have included this chapter in the coastal and marine spatial management section of the book, but we put it here because of the emphasis on a visual resource scenic-quality inventory of publicly accessible viewpoints of the territorial sea, the adoption of visual class standards, and the modeling of viewsheds and viewshed class values. As such, the use of visualization tools described in this chapter may provide an important exemplar for other coastal states that are seeking to bring public participation and community values into the spatial framework for decision-making, thereby helping communities to define and conceptualize management, sustainability, and resilience.

Chapter 16 (updated in the second edition) returns the discussion to server/cloud GIS while drawing also on the theme of visualization. The chapter presents workflows using ArcGIS 10.2 GeoEvent Extension for Server as well as a series of Python scripts to map, in near real time, the observations of wave and profile gliders monitoring the shallow water depths of the Gulf of Mexico. Researchers will apply this process to visualize future observations from these platforms, which are critical for understanding and reducing ocean acidification and oxygen-poor conditions in the Gulf.

Chapter 17 ushers in brand-new content for the second edition with an overview of seamounts: how they are officially defined as features on the ocean floor, how they are mapped and classified, and why they are an important foundation for marine habitat protection. The chapter presents a new seamount classification scheme based on multivariate analysis of differences in area, height, peak depth, proximity to nearby features, and the area of steep slopes. A focus on seamount types within the Clarion-Clipperton Zone in the eastern Pacific Ocean and Kiribati's marine jurisdictions evaluates the usefulness of the classification for improving existing management regimes and setting future management priorities.

Chapter 18 provides an overview of the benefits of using satellite image analysis and web services for a range of coastal applications, from mapping the shallow water bathymetry of the Great Barrier

Reef, to exploring the seafloor habitats of Abu Dhabi, to recording various inland water quality sites, to monitoring dredging sites. Chapter 19 introduces the reader to The Nature Conservancy's Coastal Resilience suite of web-based tools for examining coastal hazards as well as social, ecological, and economic assets. It also includes one of the more extensive sets of supplemental materials, featuring interactive learning modules, sample datasets, a full GitHub repository of computer code, and "digital stories" in video mode.

Chapter 20 continues the thread of coastal resilience by describing collaborations among county regional planners and scientific and policy experts to shape climate adaptation planning at various scales throughout coastal California. The team conducted a spatially explicit coastal vulnerability assessment using the Natural Capital Project's InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) tool and ArcGIS with an eye toward evaluating the role of natural habitats in reducing exposure to rising sea levels and increasingly intense storms.

The author team for chapter 21 included several undergraduate students at the University of Redlands and chronicles their geospatial adventures while participating in a travel course to French Polynesia to study various applications of environmental science on the atoll known as Tetiaroa. This adventure was more than just a field trip. The students and faculty studied one of the last ground-nesting bird populations on Earth as well as ongoing changes in shoreline position to evaluate overall island geomorphology, all using kite aerial photography and GIS.

Chapter 22 returns to the theme of seafloor classification, but by way of bathymetric features that are probable modern-day paths for sediment drainage (i.e., canyons, valleys, channels, funnels, chutes, and hollows carved out by downslope sediment gravity movement, wave or current traction, and liquefaction). Identifying these pathways is important for understanding the supply of nutrients to benthic habitats and related controls on benthic community structure and biomass.

Finally, chapter 23 introduces the Navy Shore Geospatial Energy Module, a platform to help the US Navy become more resilient to climate change through reduced energy consumption, the integration of alternative energy sources, and ultimately the enhancement of energy security through sustainable energy usage. This platform, unique among the US Armed Forces, enables navy installation managers to track and map energy usage while geodesigning energy conservation projects and facilities management scenarios.

May this book not only inspire #OceanOptimism but drive real action with GIS. Such action needs a continued infusion of ideas and best practices. Hence, we envision *Ocean Solutions, Earth Solutions* as evolving into a series of research monographs, always based on Esri Ocean GIS Forum events as they continue to evolve.

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CHAPTER 1

Cloudy with a Chance of Fish: ArcGIS for Server and Cloud-Based Fisheries Oceanography Applications

Tiffany C. Vance, Stephen Sontag, and Kyle Wilcox

Abstract

Wright et al. (2013) defined cyber-GIS as “GIS detached from the desktop and deployed on the web.” This chapter describes two cyber-GIS applications—the Ecosystems Fisheries Oceanography Coordinated Investigations Data Access and Analysis Tool and LarvaMap—developed for data integration and particle modeling in support of fisheries oceanography research and fisheries management. Both were developed to make it easier for researchers to locate, link, analyze, and display in situ and model data. Because geospatial/temporal relationships are critical in understanding the early life history of commercially valuable fish species such as walleye pollock (*Gadus chalcogrammus*), integrating the generation of model results and in situ environmental data using GIS provides critically needed tools.

The Ecosystems Fisheries Oceanography Coordinated Investigations Data Access and Analysis Tool uses an ArcGIS for Server front end for selection, display, and analysis of data stored in an Oracle database. LarvaMap is a cloud-based tool for running particle dispersion models for fish and invertebrate larvae. It supports scenario testing and makes it easy for nonmodelers to configure and run models. The front end is a web-based map interface, and running the tracking model in a cloud resource allows scaling of computer resources to meet computational needs. Both applications provide basic display and analysis of data and can be integrated with desktop GIS for advanced analyses and two-, three-, and four-dimensional visualizations. The results from these projects can be translated to other types of particle tracking, other data management needs for environmental studies, and used as case studies of deployment of GIS tools to cyber-GIS computing resources.

Problem and Challenge

Knowledge of the complex relationships between the targeted fish species and its food sources, predators, and environment will aid the new emphasis on ecosystem-based approaches to fisheries management (Link 2002). Understanding these relationships can guide the management of a fishery and the setting of quotas, timing of fishing periods, and management of related fisheries or species that depend on the target species. Investigating these relationships requires a combination of field research and computer modeling. Field research gathers large amounts of disparate data that needs to be managed, integrated, analyzed, and visualized. Many times, the only common characteristic of this data is the fact that it can be geolocated. Spatial analyses and geospatial measures are critical in understanding this data. Models of ocean circulation, fish life histories, or complicated ecological interactions can require huge amounts of computing resources, generate massive output files, and be best understood using advanced visualization and analysis tools.

Providing the computational and analytical environment to support these studies is challenging. Local desktop resources are frequently insufficient. Tightly focused databases can make integrating information almost impossible, and visualization tools may be hard to use. New developments in cyber-GIS, specifically the expansion of ArcGIS for Server and increased access to cloud computing resources, have enabled us to develop and test a number of applications to address solutions for integrating disparate data for easy retrieval and analysis using ArcGIS for Server, either locally or in the cloud, and explore the possibilities of running models in the cloud and storing and displaying their results in a geospatially enabled application.

Introduction and Background

Parallel technological advances in computing and marine fisheries research have contributed greatly to truly implementing ecosystem approaches to fisheries management. Technologies first developed during World War II have been used both to improve sampling in marine systems and support modeling and geospatial analyses. Military surplus vessels formed the core of the oceanographic and fisheries research fleet in the 1950s and onward (Rainger 2000; Rozwadowski and Van Keuren 2004; Hamblin 2005), sound navigation and ranging (SONAR) techniques were adapted to become the core of fisheries hydro acoustics (Fornshell and Tesei 2013), and biological sampling became increasingly electronic (Dickey 2003; Wiebe and Benfield 2003). Computing resources evolved from large mainframe computers to minicomputers and personal computers, to computers on a chip embedded in deployed instruments, and finally back to large centralized, elastic computing resources in the cloud. Geospatial analysis has gone from the early days of GIS in SyMAP and the Canada Geographic Information System (Coppock and Rhind 1991) to ArcInfo to open-source GIS, cyber-GIS, and ArcGIS for Server providing GIS in the cloud.

GIS and other spatial analysis tools provide important tools to understand natural systems. The advent of cyber-GIS has made these tools even more powerful by removing constraints on the size and complexity of analyses through elastic computing resources and cloud-based storage for terabytes of data. Of course, what has been called the “grand challenges” remain, of data intensity, computing intensity, concurrent intensity, and spatiotemporal intensity (Yang et al. 2011). The data integration and complex system modeling tools we have created with the Ecosystems Fisheries Oceanography Coordinated Investigations (EcoFOCI) Data Access and Analysis Tool (EcoDAAT) and LarvaMap take advantage of early answers to these challenges.

Wright et al. (2013) have written of cyber-GIS as GIS removed from the desktop to centralized, usually cloud-based resources. Wang et al. (2013) describe cyber-GIS as “cyberinfrastructure-based GIS” and a subset of the broader realm of “spatial cyberinfrastructure” as defined in Wright and Wang (2011). Yang et al. (2013) have identified a number of disciplines in which cyber-GIS can support critical advances. Topics related to fisheries include climate science, ecology, environmental health, and disaster management. They call for advancements in system architectures, which can directly support modeling and visualization and are key to understanding the outputs of complicated ecosystem models; data storage, which will support both the storage of field data and outputs of models; and data and process colocation, which may be less critical because of developments such as the grid caching we developed for LarvaMap described later in this chapter (Yang et al. 2013).

Nyerges (2010) specifically addresses the application of cyber-GIS to marine systems by looking at uses of cyber-GIS for modeling coastal marine policy and governance. Although his focus is on human communities, many of the elements he cites are equally applicable to marine ecosystems that also have a “large number of interacting components,” creating systems that are “computationally complex and intense” with spatiotemporal elements that “require tremendous amounts of data and computational support.” EcoDAAT uses the cyber-GIS concepts of moving processing and data storage from the desktop to a centralized resource with a web-based thin client providing the user interface. The results can be used either for analyses via ArcGIS for Server or for local GIS or statistical analyses using ArcGIS or tools such as R. LarvaMap takes advantage of cloud-based computing resources by running its models on a cloud computing resource. The ability to launch additional model runs in the cloud provides easily scalable computer resources, and data can be stored either in the cloud or in local Open-Source Project for a Network Data Access Protocol (OPeNDAP)/Thematic Real-Time Environmental Distributed Data Services (THREDDS) servers. Both of these tools help meet the ecosystem-based management needs of integrating field data with models, integrating physical and biological data, and providing information on the early life history of commercially important species.

History and Status of the Walleye Pollock Fishery in Alaska

EcoDAAT and LarvaMap are first being applied to studies of the early life of walleye pollock (*Gadus chalcogrammus*), hereafter simply *pollock* (figure 1.1). Pollock are a groundfish found primarily in the North Pacific and Bering Sea that supports the largest commercial fishery in the United States by weight (Kendall et al. 1996; AFSC 2013). The primary human uses of pollock are in making fish sticks and fish sandwiches, and as surimi to make imitation crab. Juvenile pollock are a critical food source for flatfish (Lang et al. 2000), and adult seabirds serve as food for Pacific cod, Pacific halibut, sea lions, and other marine mammals.



Figure 1.1. Walleye pollock larvae, adults, the products made from pollock, and major predators of pollock.
By Ingrid Spies and other photographers from the Alaska Fisheries Science Center, NOAA Fisheries Service; additional photograph by Nazila Merati.

In the Gulf of Alaska, pollock start as eggs spawned in March and April. The eggs are spawned at a depth of 100–250 m and hatch in two to three weeks. Larvae occur at an average depth of 40 m and develop over the next few months. At this stage, they are still at the mercy of oceanic currents and transported as though they were inanimate particles. Once the larvae are about 60 days old, they develop rudimentary swimming skills. Though not able to swim long distances, they are able to swim in bursts to consume prey and avoid potential predators. After 100 days, they are competent swimmers and can move up and down through the water column. At the age of three or four years, they are large enough to be commercially harvested and reach sexual maturity at age four or five. They can live for more than 20 years, but fish that old are unusual (AFSC 2010).

The Gulf of Alaska and Bering Sea pollock fishery started with a small trawl fishery in the 1950s, and catches increased rapidly in the 1970s and 1980s as the foreign fishing fleet targeted the population. The discovery of a spawning population of the fish in Shelikof Strait in 1981 led to the development of a roe fishery. Intense fishing in the international waters of the Donut Hole area of the western Bering Sea in the 1980s led to the collapse of that pollock population (Bailey 2013). By 1988, changes in fisheries regulations excluded the foreign fleet from American waters and transformed the pollock fishery into a domestic US fishery with the primary consumer products being frozen filets and surimi. In the 1990s, the rise of ecosystem-based management led to consideration of related species in managing the fishery; and in 1999, the Aleutian Islands portion of the fishery was closed in response to declines in Stellar sea lion populations, with the thought that fishing was

overcompeting with sea lions for fish (National Research Council 2003). This fishery was reopened in 2005 (AFSC 2010). A complete history of the fishery, both domestic and international, can be found in Bailey (2013).

Management of the fishery depends on, among other things, an understanding of the early life history of pollock. Success in the early stages of life is one factor determining how many fish are eventually available to be harvested while preserving a sustainable population. The EcoFOCI program at the National Oceanic and Atmospheric Administration (NOAA) studies the factors that affect the variability in recruitment of pollock and other commercially harvested species in the Gulf of Alaska, North Pacific, and Bering Sea. Oceanographic and biological factors are studied using a combination of field and model studies. Field research includes physical oceanographic surveys and biological sampling to look at life stages from eggs to juveniles and post-age-1 fish. A particular emphasis of the sampling is studying pollock early life history. The zooplankton that supports the fish populations is also sampled and described. The samples collected also support age and growth, genetic, and food habit studies. The field data supports an understanding of the biological and physical factors affecting recruitment. The data also provides initial conditions and validation for model studies.

Understanding the Early Life History of Pollock Using Individual-Based Models

One of the “grand challenges” in fisheries research is understanding the fluctuations in the size and structure of fish stocks. The classic work by Hjort (1914) described two hypotheses to explain the variability: The first, the Critical Period hypothesis, posits that the size and strength of a year class of fish is determined very early in life, when the fish have exhausted their yolk sack and started feeding, and is a function of the availability and quality of the plankton they are feeding on. The second, the Aberrant Drift hypothesis, examines the role of transport in taking fish larvae so far from place of birth that they are unable to return to support future populations. A variety of hypotheses has developed in the century since Hjort’s work, including the Match-Mismatch hypothesis of Cushing (1974), which relates the timing of larvae hatching and bloom of plankton to feed them; the effect of vertical stratification in the Stable Ocean hypothesis of Lasker (1978); and a number of other hypotheses described and related in Houde (2008) and Hare (2014).

In studies of marine fish recruitment, early studies to test hypotheses were primarily descriptive and considered aspects such as the scale of distributions of plankton (Haury et al. 1978). More recently, advances in the collection of quasi-synoptic in situ and satellite data, the rise of ecosystem approaches to studying marine systems (Levin 2006; Vance and Doel 2010), and rapid and striking advances in computers and data storage (Gentleman 2002; Yang et al. 2011) have radically changed research on recruitment. Hydrodynamic models are now able to resolve details at the scales that affect recruitment (tens of kilometers), and they can be run for weeks to months of model time to cover the early life history of slowly developing species. Biological and physical processes can now be coupled and modeled, and advances in visualization tools have made visualizing and interpreting large model outputs easier (Megrey et al. 2002; Vance et al. 2006; Vance 2008).

One requirement that these various hypotheses share is a need to know where fish larvae are located at various stages of life. This need has led to the development of techniques to model the dispersion of larvae based on hydrodynamic models of the ocean. At their simplest, these models distribute larvae as though they were inanimate particles drifting in ocean currents. More detailed models include larval behaviors such as the ability to swim, motion toward or away from light, and avoidance of warm or cool water (Hinckley et al. 1996; Hermann et al. 2001; Miller 2007;

Hinckley et al. 2009). These models are the simplest of what are called *individual-based models* (IBM), which are called *agent-based models* in other disciplines. An example is the DisMELS model (Dispersal Model for Early Life History Stages), which incorporates behavior in early life stages to study the dispersion of eggs and larvae (Stockhausen 2006). More complex models describe both larval distributions and the distributions of prey for the larvae. These tools, often called *nutrient-phytoplankton-zooplankton* (NPZ) models, describe spatial and temporal interactions (Franks 2002). Upper-trophic level models such as FEAST (Forage and Euphausiid Abundance in Space and Time) add predator and bioenergetic parameters (Aydin et al. 2010; Ortiz 2014).

Integrating and Analyzing Field Data using EcoDAAT

Web-based GIS applications for data discovery and marine planning encompass a wide range of tools. SeaSketch (<http://mcclintock.msi.ucsb.edu/projects/seasketch>) supports collaborative design but does not support data storage or analysis. SIMoN (http://sanctuarysimon.org/regional_sections/maps/mpaviewer/) and similar tools provide mapping of the location of data collection sites and links to project websites but do not allow for analysis of the data. GIS-based data discovery/download-only tools, such as many of those listed for ecosystem-based management (EBM) on the EBM Tools Network (http://www.ebmtools.org/?q=ebm_tools_taxonomy#), acquire and manage data but do not focus on geoanalysis. The strength of EcoDAAT is that it allows location and downloading of raw data as well as simple geoanalysis.

Because the field sampling for EcoFOCI work on pollock and other forage species is multidisciplinary, the datasets gathered are in disparate formats. The datasets for ichthyoplankton, zooplankton, and environmental measurements were originally stored in separate Microsoft Access databases. This made it hard to answer questions such as “What are the water temperatures where we find larger than average pollock larvae?” in a timely manner. Although the datasets were not enormous—the largest had about 250,000 records—network response time made it impractical to store the data in a single shared database on a network drive. Rather, it was necessary to have the complete databases on the desktop system of each user. This maintenance challenge caused databases to get out of sync if updates failed or were delayed. The physical oceanographic datasets of EcoFOCI collaborators contain up to six million conductivity-temperature-depth (CTD) records, making it impossible to deploy them as part of the existing databases.

The project to create EcoDAAT had a number of goals: to integrate the databases so that cross-data-type queries were possible, move the integrated database to a larger and more robust database application, and make the data selection and display more geospatial by providing a map-based interface and ArcGIS for Server-based analytical tools. To meet these goals, an ArcGIS for Server/Flex front end connected to an Oracle database was chosen. The system layout is shown in figure 1.2. The datasets are stored in a single Oracle database designed to contain, and link, the various types of data being collected. The data cascade is started at sea, where a stand-alone Java/SQLite application called the Cruise Operations Database (MasterCOD) is used to input metadata and collection information about every operation. The information includes the latitude and longitude of the operation, time and date, type(s) of equipment deployed, types of sample(s) gathered, and any notes about the operations. These records are used to track samples as they are analyzed and also to geolocate and cross-reference operations and samples. These datasets are used to populate the Haul tables of the Oracle database with core information and also to populate tables in two associated applications, ZooPPSI and IchPPSI. These two Java/SQLite applications are used by researchers at the Polish

Plankton Sorting and Identification Center to record identifications and measurements of zooplankton and ichthyoplankton in samples sent to them for processing. Data from completed ZooPPSI and IchPPSI tables is loaded into the EcoDAAT Oracle tables using a series of Standard Query Language (SQL) scripts. These datasets are used to populate sample and specimen tables and associated tables to hold species and diet information. Information on larger age-0 and older fish collected during trawling operations is stored in Microsoft Excel spreadsheets at sea. The datasets are loaded into the Oracle database in a similar process to the loading of ichthyoplankton data. Laboratory analyses of stomach contents and other diet and condition-related information are loaded from text files and spreadsheets. Physical oceanographic datasets, including CTD and SeaCAT measurements, are processed using Sea-Bird Electronics files, reformatted into comma-separated value (CSV) files, and loaded using SQL scripts. Both CTD and bottle datasets are stored and can be linked to sample data.

The EcoDAAT front end uses the Flex viewer available with ArcGIS for Server (figure 1.2). This was chosen for ease of implementation and enhanced functionality. The front end allows for data selection by type of data (e.g., ichthyoplankton or oceanographic data), geographic location using graphic- or text-based searches, time of collection, and combined criteria. The interfaces for data selection are dynamic, and the available selection criteria vary based on the type of selection being made. Because some of the data in EcoDAAT is still undergoing quality assurance/quality control (QA/QC), the front end uses Lightweight Directory Access Protocol (LDAP) authentication for secure access. In the future, a tiered access scheme—in which data can be made fully public, shared with collaborators only, or limited to program scientists—will be implemented.

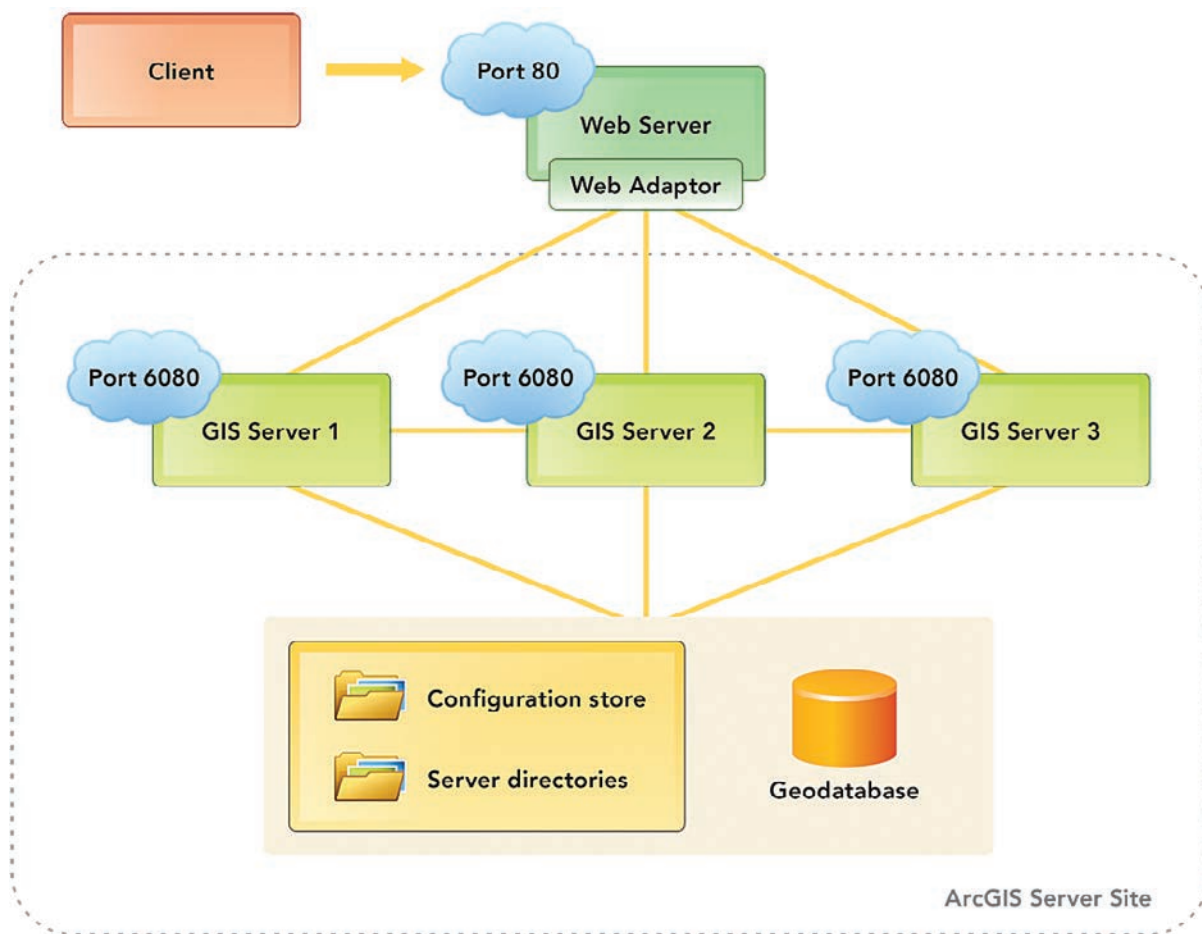


Figure 1.2. EcoDAAT system architecture showing integration of Flex, Oracle, and ArcGIS for Server. Esri.

The results of a search are available both in summary form on the map portion of the front end (with data locations highlighted and the standard GIS Identify tool implemented to query data) and as a table that can be output as a shapefile or .csv file for further analysis (figure 1.3). The results of a search for haul information can also be linked to searches for associated data to create complex queries.

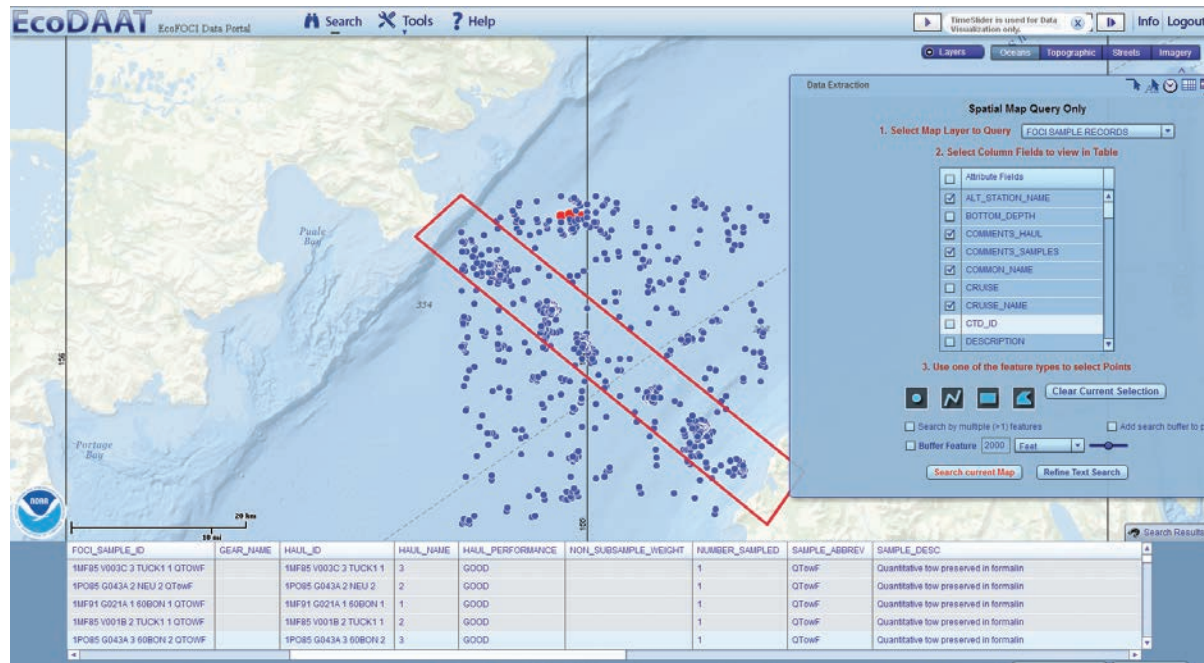


Figure 1.3. Example of the map-based selection tool in the Ecosystems Data Access and Analysis tool (EcoDAAT) and a table of data. By NOAA Alaska Fisheries Science Center; data sources: NOAA Alaska Fisheries Science Center, Esri, DeLorme, GEBCO, NOAA NGDC, National Geographic Society, HERE, Geonames.org, and other contributors.

Simple geoanalyses such as creating and plotting a bathymetric cross section are available (figure 1.4). These types of tools will be expanded in the future by taking advantage of the geoprocessing tools available in ArcGIS for Server.

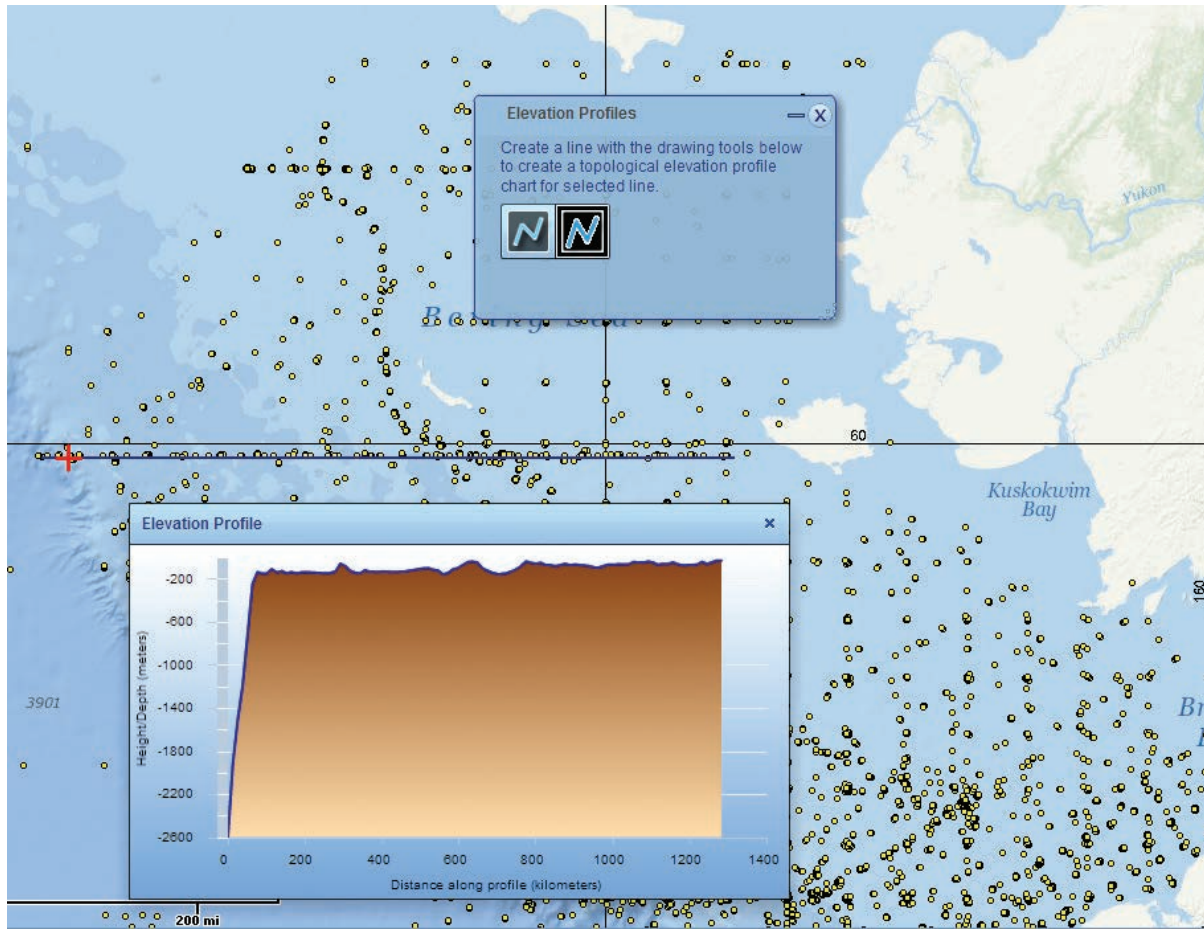


Figure 1.4. Example of the cross section tool in EcoDAAT. By NOAA Alaska Fisheries Science Center; data sources: NOAA Alaska Fisheries Science Center, Esri, DeLorme, GEBCO, NOAA NGDC, National Geographic Society, HERE, Geonames.org, and other contributors.

Tracking the Transport and Dispersion of Larvae Using LarvaMap

Particle-tracking models enable the study of the motion of particles in the atmosphere or the ocean, from oil globules from an oil spill to plumes of smoke or sediment to even the ash from a volcanic eruption. Many models run locally and require setting up complicated parameter files for a model run. Examples include the Ichthyop tool for Lagrangian modeling of the Bay of Biscay and Mediterranean Sea (Lett et al. 2008) and the Lagrangian Transport Model (LTRANS), which was originally created to model the dispersion of oyster larvae in Chesapeake Bay (<http://northweb.hpl.umces.edu/LTRANS.htm>). Model runs can take hours to days to complete, depending on the number of particles released, duration of the run, and power of the underlying computer(s). There are an increasing number of web-based particle-tracking models, including the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) Volcanic Ash Model (Draxler and Rolph 2003), which allows users to model ash transport from a list of volcanoes using one of five common atmospheric models. Connie2 (<http://www.csiro.au/connie2/>) allows the user to set up and run particle-tracking models for the seas around Australia and the Mediterranean Sea. Connie2 allows for either passive/inanimate particles or particles that show limited behaviors such as the ability to swim.

Particle tracking is a critical element of modeling the early life history of pollock and other commercially important species. The models can be as simple as one that tracks inanimate particles and as complex as one that describes the interactions at many trophic levels in an ecosystem. Lagrangian models follow an individual through space and time by calculating a path line and tracking the motion of the particle. Eulerian models use positions on a fixed spatial grid and streamlines to describe transport through the location. LarvaMap is a cloud-hosted implementation of a Lagrangian particle-tracking model that supports a variety of behaviors in a target species. It is an individual-based model capable of using output from a variety of ocean circulation models to drive the dispersion and movement of particles. The front end is a series of web pages for setting up larval behaviors, choosing the circulation or hydrodynamic model, configuring the model run, and launching the run. The model itself is run on a cloud computing resource (currently the Amazon cloud), but it could also be configured to run on a local resource or private cloud. The results are visualized as a track line in the web client, and results are available as an Esri shapefile and network Common Data Format (netCDF) file for further analysis.

LarvaMap is a combination of four pieces of technology working together (figure 1.5), consisting of

- A behavior library to create, catalog, and share larval behaviors: <http://behavior.larvemap.axiomdatascience.com>
- A fate and transport model written as a Python library: <http://bit.ly/16dFk9x>
- A model service implementing the fate and transport model in a cloud architecture
- A web client for interacting with the Model Service through a representational state transfer application programming interface (REST API): <http://bit.ly/14aZinD>

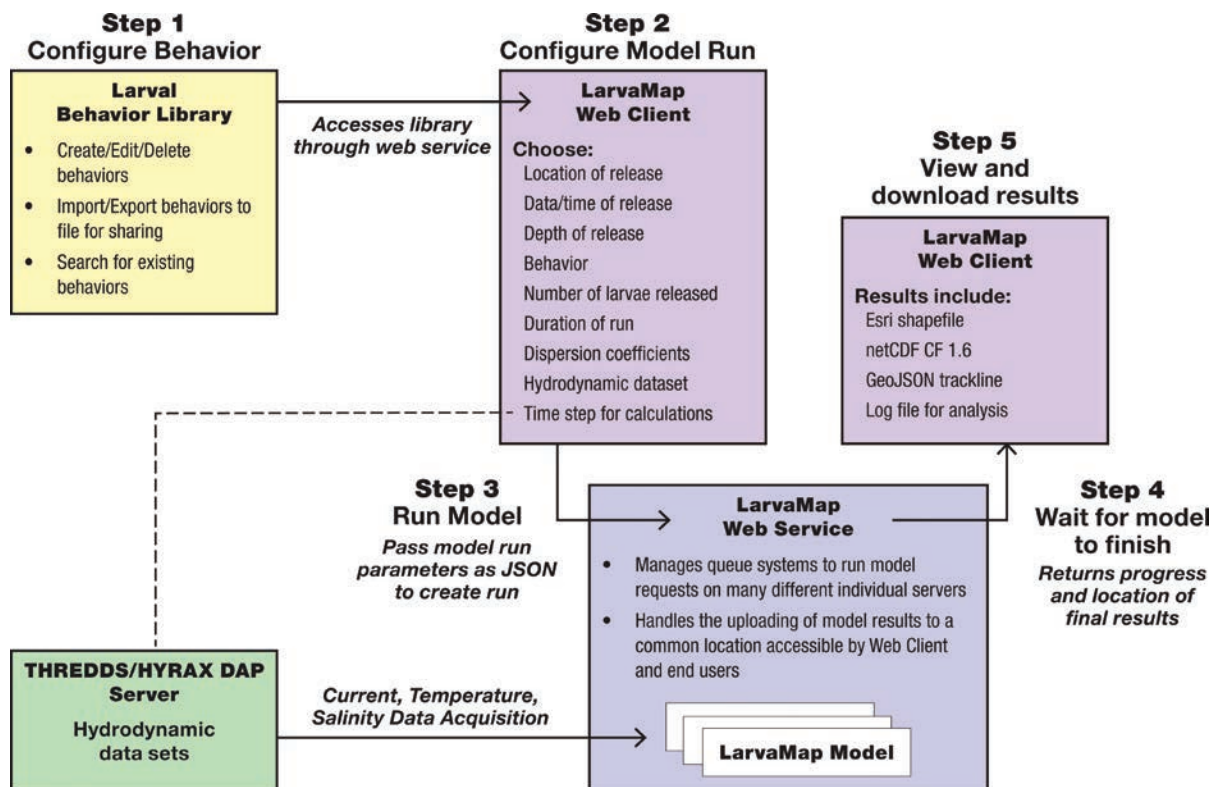


Figure 1.5. LarvaMap architecture that shows the interconnections between the various elements and the process of creating a model run. RPS/ASA.

Setting Larval Behaviors using the Behavior Library

The first step in running LarvaMap is discovering or creating a set of larval behaviors for an organism or species of interest using the Larval Behavior Library (figure 1.6). The library allows the creation of new behavior files, searching for existing files, and sharing files. Allowing behaviors to be exchanged between researchers, modelers, and students supports the creation of behaviors as a social process, with the ability to see how others have defined behaviors, to run models using both your own and community behavior files, and to work collaboratively on building behaviors. With the ease of running the models, it is possible to quickly and easily compare the results of different behaviors.

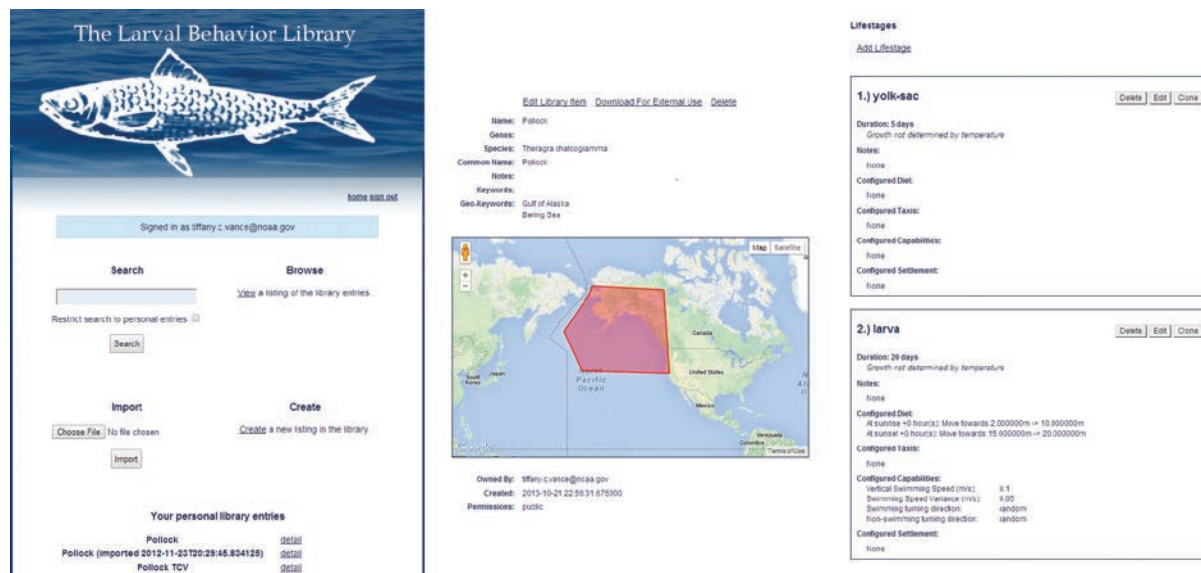


Figure 1.6. The interface to the Larval Behavior Library is used to define the behaviors of a specific species.

By NOAA Alaska Fisheries Science Center; data sources: NOAA Alaska Fisheries Science Center, Esri, DeLorme, GEBCO, NOAA NGDC, National Geographic Society, HERE, Geonames.org, and other contributors.

Behaviors that can be defined include

- The geographic range of the organism and any keywords to be used for regional searches
- Adding life stages (e.g., egg, larval, juvenile) with associated duration in days or by temperature range
- Adding behaviors to life stages, including capabilities such as swimming speed and vertical migration, reactions such as avoidance behaviors, and sensory reactions such as avoiding salinities or temperatures
- The timing of the transition out of the plankton stage and where the organism will end up—settling on the bottom for benthic species and where in the water column pelagic species will reside

Configuring the Model Run Using the Web Client: Setting Parameters and Choosing Circulation Models

Configuring the model requires setting the location, date, time, and depth of the release and specifying the number of particles to be released. The behavior model is specified, usually by species. Vertical and horizontal dispersion coefficients can be set, and the underlying hydrodynamic model

is specified (figure 1.7). Finally, the time step for the model runs is specified. Model durations of months and years can be supported, but the time step for the model must be selected to be reasonably small to provide the level of detail needed without requiring the calculation of an unnecessary number of time steps.

LarvaMap 1 Behaviors 2 Edit Behavior 3 Forcing 4 Release Config Model List EXIT

Available Behaviors

Choose One Behavior

Search Behaviors: ☒ Search Public Behaviors

Name	Genus	Species	Common Name	Created	Notes	Status	User
Pacific Herring	Clupea	Pallasi	Pacific Herring	11/14/2012 at 17		public	france@research42.org
Pacific Herring	Clupea	Pallasi	Pacific Herring	11/14/2012 at 17		public	ni@research42.org
Pacific Herring	Clupea	Pallasi	Pacific Herring	11/15/2012 at 10		public	machroeder@esa
Pacific Herring	Clupea	Pallasi	Pacific Herring	11/15/2012 at 11		public	machroeder@esa
Pacific Herring	Clupea	Pallasi	Pacific Herring	11/16/2012 at 09		public	machroeder@esa
Pacific Herring	Clupea	Pallasi	Pacific Herring	11/16/2012 at 15		public	ni@research42.org
Pacific Herring	Clupea	Pallasi	Pacific Herring	11/16/2012 at 16		public	ni@research42.org
Pollock	Theragra	chalcoides	Pollock	10/21/2013 at 16		public	tiffany.c.vance@noaa.gov
Pollock (imported)	Theragra	chalcoides	Pollock	11/23/2012 at 12		public	tiffany.c.vance@noaa.gov
Pacific Herring (f)	Clupea	Pallasi	Pacific Herring	04/23/2013 at 05		public	wilcox.kyle@gmail
Testing Del	Melanurus	Geronemus	Mel	04/23/2013 at 05		public	wilcox.kyle@gmail

☐ Edit Behavior

General Distribution Region

Forcing

Choose a Currents Dataset

Name	Start Time	End Time	Last Updated	URL
Prince William Sound - Forecast - L1	01/01/2011 at 22:00	10/01/2013 at 23:00	08/17/2013 at 02:25	http://trhredds.axiomalaska.com/trhredds
Prince William Sound - Forecast - L2	01/01/2011 at 22:00	10/11/2013 at 23:00	08/17/2013 at 02:30	http://trhredds.axiomalaska.com/trhredds
Prince William Sound - Nowcast - L1	03/30/2009 at 23:00	09/29/2013 at 23:00	08/17/2013 at 02:20	http://trhredds.axiomalaska.com/trhredds
Prince William Sound - Forecast - L2	01/03/2011 at 22:00	10/01/2013 at 23:00	08/16/2013 at 01:22	http://trhredds.axiomalaska.com/trhredds
NCOM - Region 7 (West Coast)	12/31/1999 at 16:00	03/21/2013 at 17:00	09/26/2013 at 11:55	http://ecowatch.nodc.noaa.gov/trhredds
NCOM - Global Surface (2009-2013)	05/02/2009 at 17:00	03/22/2013 at 17:00	09/27/2013 at 07:02	http://ecowatch.nodc.noaa.gov/trhredds
NCOM - Arneass - 2009 to 2013	05/07/2010 at 17:00	04/04/2013 at 14:00	10/01/2013 at 09:39	http://ecowatch.nodc.noaa.gov/trhredds

Run Model

Choose Model Items

Model Name:

Start Date:

Duration: days

Total Time Step: mins hrs days

Total Minutes:

Method:

Particles:

Release Depth: meters below surface - positive down

Horizontal Dispersion: m/s

Vertical Dispersion: m/s

Select a point on Map. Showing Forcing Domain on map. Location: Lat: Long:

Figure 1.7. The interface for configuring and running a LarvaMap model. By NOAA Alaska Fisheries Science Center; data sources: NOAA Alaska Fisheries Science Center, Esri, DeLorme, GEBCO, NOAA NGDC, National Geographic Society, HERE, Geonames.org, and other contributors.

Hydrodynamic models include those provided via THREDDS/OPeNDAP server or available as a local file. OPeNDAP and file-based datasets can be added to the LarvaMap system as they are discovered. An administrator of the LarvaMap system can add a dataset through an interface, and datasets must be registered in LarvaMap before they can be used for particle forcing. Both local and OPeNDAP datasets can be registered in LarvaMap. A Python library called *paegan* (<https://github.com/kwilcox/paegan>) was developed as part of the LarvaMap project to facilitate consistent access to many formats of hydrodynamic model data. If the dataset opens in *paegan* as a *CommonDataset* object, it is usable in LarvaMap. Currently, *paegan* supports regular grids ($\Delta y == \Delta x$), curvilinear grids (sometimes called *i/j grids*), and static triangular meshes. Dynamically changing grids and nontriangular meshes are not yet supported. LarvaMap does not support uploading of any ocean circulation data files for internal storage. File-based datasets must be made accessible to all model runs in the LarvaMap architecture before being used. Installations of LarvaMap that use the distributed file system GlusterFS can achieve this.

The Regional Ocean Modeling System (ROMS) and US Navy Coastal Ocean Model (NCOM) models have been used to look at transport of pollock and herring in the North Pacific. Lowry (2013) used LarvaMap linked to an ROMS model for Prince William Sound to model drift and recruitment of herring. The NCOM region 7 model has been used to look at transport of sea urchin larvae off the California coast. The NCOM AmSeas model has been implemented for use in the Gulf of Mexico.

The Heart of LarvaMap: Fate and Transport Models

During a model run, the transport process is broken into smaller fragments called *models*. Each model implements a *move* method that moves a particle based on environmental and behavioral properties. Each model has access to environmental conditions from the hydrodynamic model (u , v , w ; temperature; and salinity) at the current location and time of the particle. In a few specific scenarios, environmental data for a particle's location and time may be unknown: particle has left the domain of the hydrodynamic dataset, or there is a data gap in the hydrodynamic dataset. Under these conditions, the last known environmental conditions that the particle experienced are used in the model.

LarvaMap implements three main models. The models are run sequentially, and the results are checked against the shoreline and bathymetry (figure 1.8). A typical time step in a model run is as follows:

- Run transport (moves particle).
- Check shoreline.
- Check bathymetry.
- Run dispersion (moves particle).
- Check shoreline.
- Check bathymetry.
- Run behavior (moves particle).
- Check shoreline.
- Check bathymetry.

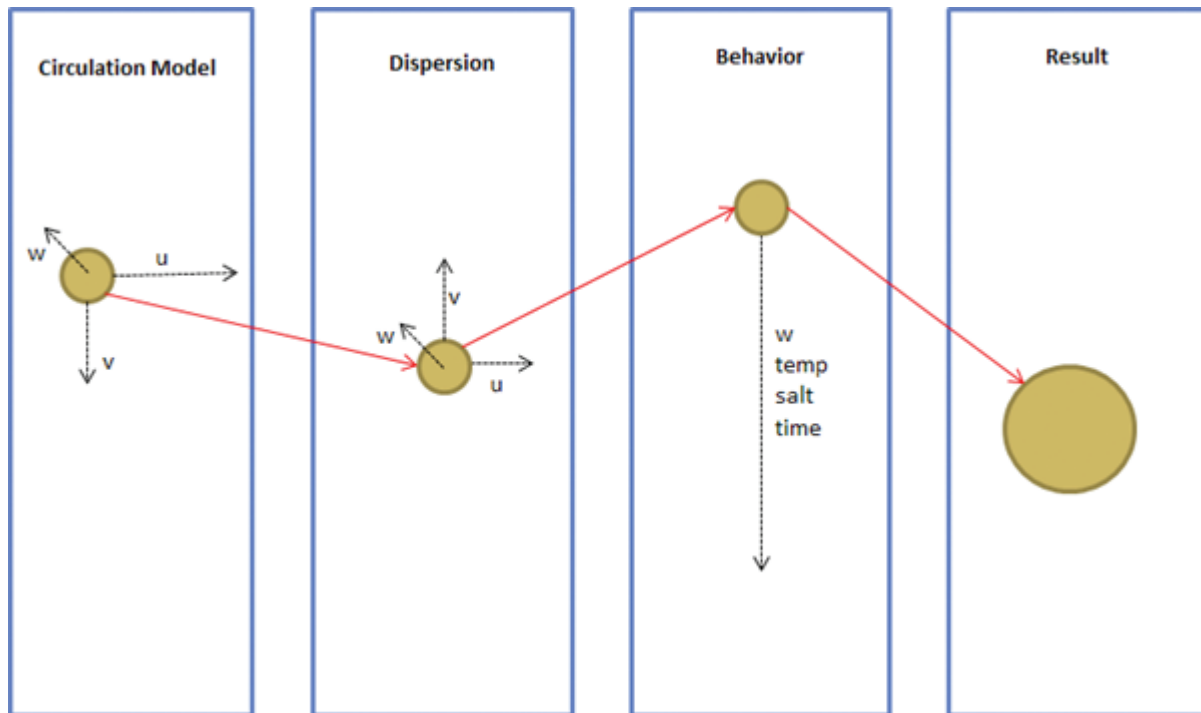


Figure 1.8. Elements of the transport process during a single time step in a model run. Variables u , v , and w are the circulation model velocity components. RPS/ASA.

Transport

The transport model for LarvaMap is a parallelized Lagrangian transport model that uses hydrodynamic circulation data stored as netCDF/OPeNDAP files. The model is written in Python and uses the paegan library, which provides a data model for ocean and meteorological data stored in netCDF files and the paegan-transport libraries for the model itself. It moves a particle based on the current velocity components (u [zonal or east–west], v [meridional or north–south], and w [vertical]) from the hydrodynamic model. The vertical component (w) is optional. If the transport model receives no u , v , or w data for the place and time of the particle, the last known conditions are used.

Dispersion

Each model run is configurable using a horizontal and vertical dispersion coefficient (in m/s). These coefficients are used to compute the u , v , and w dispersion.

Behavior

The behavior model is set up using a configuration from the Larval Behavior Library. A configuration consists of many life stages, each with its own behaviors. The behavior model is responsible for calling the correct life stage model based on such factors as a particle’s development, age, and mass, and adding a “dead” life stage to every behavior configuration. This model does not actually move the particle—the life stage model does. It can be thought of as a *container* model.

Life Stage

The life stage model grows each particle based on time or as a function of temperature. It also calls the correct behavioral models associated with the particle's life stage. For example, if there are four diel behaviors configured for a single life stage, this life stage model determines which diel behavior to call based on the particle's time. The behavioral models described as follows work a bit differently from the transport and life stage models. They do not return a new location for the particle; they only return the u , v , and w vectors. The vectors are summed from all behaviors by this life stage model; and the particle is only moved once, after all behaviors are completed. If the life stage model receives no temperature or salinity data for the place and time of the particle, the last known conditions are used.

Life Stage: Diel

The diel model moves a particle up and down in the water column based on the sun's position in the sky. Each life stage of a larva has a configured static vertical swimming speed that is used here to determine how fast the particle can move to its desired depth range. If the particle's vertical swimming speed puts the particle beyond the desired depth range, the swimming speed is recomputed for a single model time step to land the particle in the middle of the desired depth range. If the desired depth range will not be reached, or the particle will end up inside the depth range, the vertical swimming speed configured in the behavior is used. A particle below desired depth will swim up, a particle below desired depth will swim down, and a particle at the desired depth will do nothing.

Life Stage: Settlement

The settlement model decides whether a particle should settle under its current conditions. As described in the Larval Behavior Library section, there are two types of settlement:

- Benthic: settles particle at 1 m above the bathymetry if the bathymetry is within the configured settlement depth range
- Pelagic: settles particle at its current depth if it is within the configured depth range

The settlement model does not return u , v , or w vectors. It directly settles or moves the particle to the desired settlement location.

Life Stage: Dead

The dead model's purpose is to kill a particle that has not settled and has aged beyond its settlement life stage. It continues to track environmental conditions around the dead particle, and the particle will continue to be forced by the other models (transport/dispersion), but the dead model always returns 0 m/s u , v , and w .

Under the Hood: Circulation, Shoreline, and Bathymetric Data for Model Runs

Hydrodynamic Caching Strategy

One of the challenges in running a particle tracking model is that the particles are sparsely distributed. The transport model supports long-running models on the order of months and years, with no upper time limit imposed by the trajectory model. Although the circulation model data

must cover a large area to support any possible particle locations, at any given time step the particles occupy a small subset of this total area. Downloading the entire circulation/hydrodynamic model data for each time step is prohibitive. But because LarvaMap allows for remote data access over the data access protocol (DAP), the entire hydrodynamic dataset for the area of interest never has to be downloaded and stored locally. The data can be accessed on the fly, and the model downloads only the data it needs to run the model (figure 1.9). Data that is downloaded by the model is reused from particle to particle, so the same data is accessed and downloaded only once. Particles use the locally cached data in forcing algorithms.

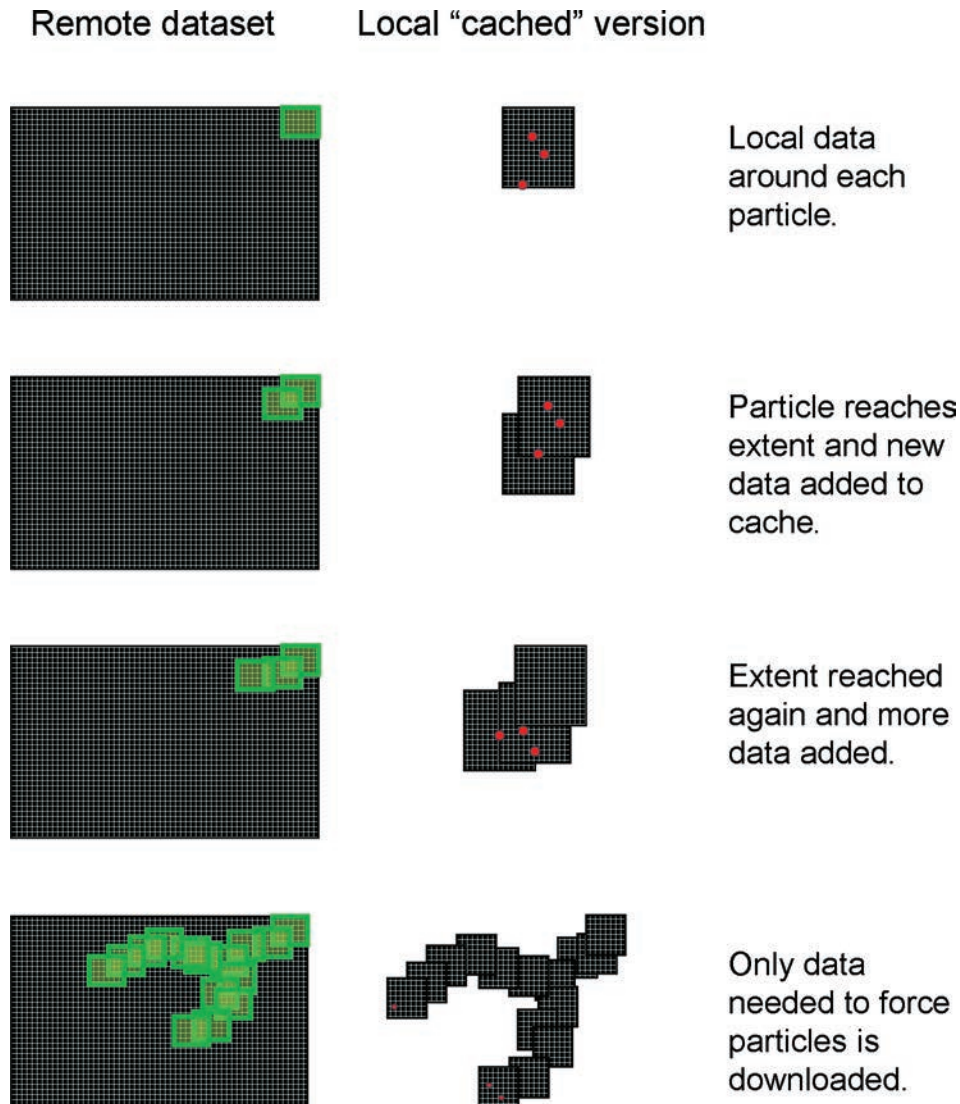


Figure 1.9. The data caching scheme used to reduce the size of downloads from the underlying circulation model. RPS/ASA.

Shoreline and Bathymetry

The fate and transport model uses land polygon objects to test for shoreline collisions. The land polygons can be stored in an Esri shapefile or accessed from an Open Geospatial Consortium (OGC) web feature service (WFS) server. Every particle loads the shoreline upon creation and indexes the

shoreline around its current location. Every time a particle tests its location against the shoreline file, it first makes sure that it has the appropriate data from the source shoreline dataset to do its calculation (figure 1.10). If it does not, it accesses the raw shoreline data, whether it is a shapefile or WFS server, and pulls a chunk of the data around its current location. This acts as a caching mechanism so that the particles are not reading from the shoreline data at every detection check. A similar process is used with bathymetric data to constrain particles to the water column.

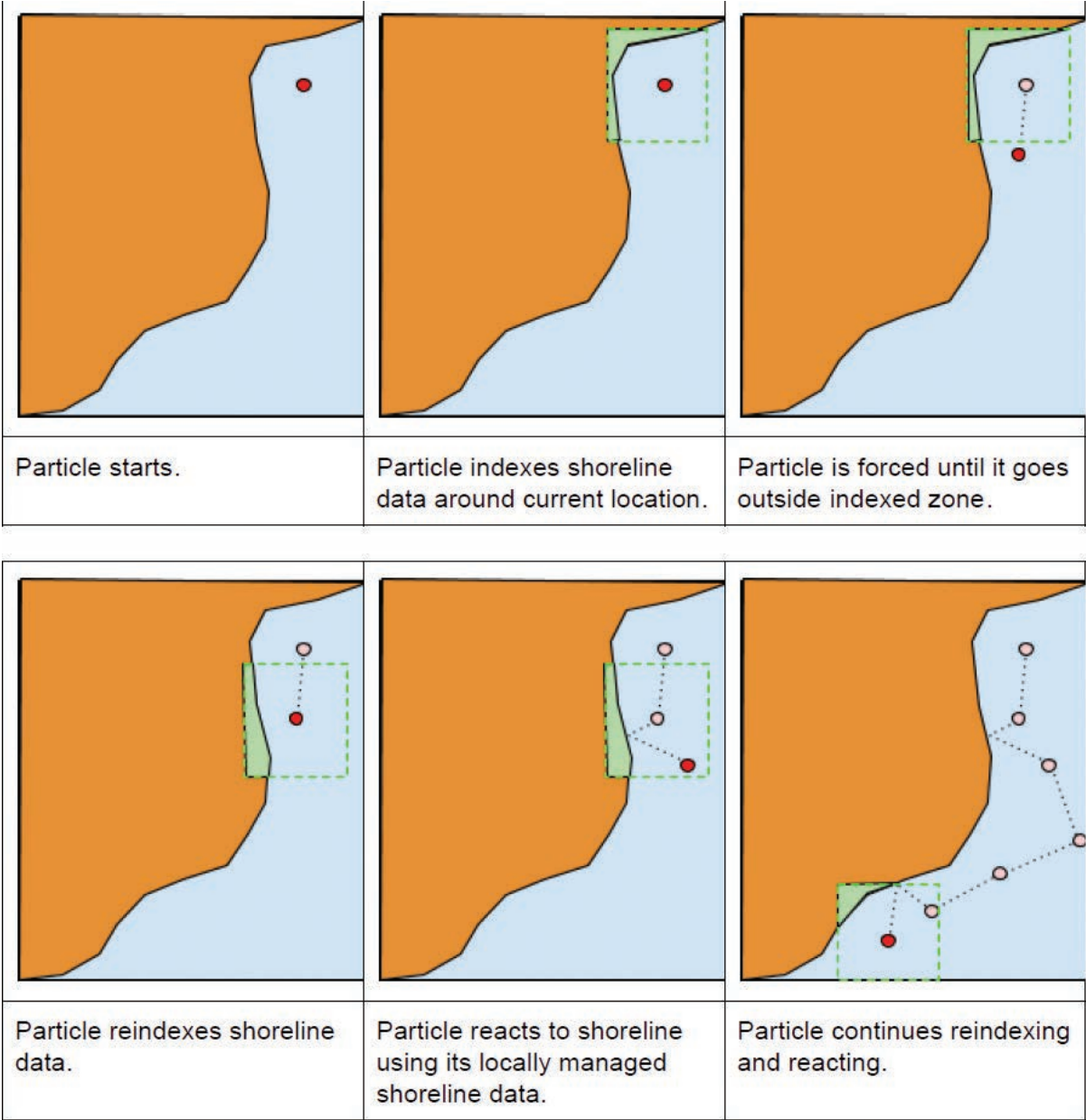


Figure 1.10. Shoreline indexing scheme used to locate the appropriate shoreline segments in the vicinity of a particle. Avoidance behavior when a particle nears a shoreline is shown in the last two parts of the figure. RPS/ASA.

The Model Service: Implementing LarvaMap in the Cloud

The model service queues model run requests received from the web client and distributes them within a network of “worker” servers. Worker servers can be running in many different places, including the Amazon cloud and local data centers. Each central processing unit (CPU) core on a worker server can force a single particle for the entire duration of its model. If 100 worker cores are available, 100 particles can be run in parallel. This can be a single model run with 100 particles, or 10 model runs with 10 particles each. The model service will automatically create new worker servers when the load demands it. Exactly when to spawn a new worker server is determined by how many particles are in the queue waiting to be run. If the number of particles in the queue is three times more than the number of CPU cores available on all worker servers, another worker server is initialized. Worker servers are shut down as the number of particles in the queue decreases. When no particles are in the queue, there is a minimum of one worker server running. Cloud computing technology allows LarvaMap to scale the number of worker servers dynamically as they are needed. In the near future, the model service will also be able to distribute a single particle’s model run onto multiple servers, which can reduce model run times to one-tenth of the current run time.

The model service collects the results from all the worker servers and pieces them together into the final results for each model run. It creates the final output formats and uploads the result files to a common location for the web client to access. Utilities are available to monitor the status of the model service currently running jobs and details about any failed jobs.

Outputs from Model Runs

Outputs from LarvaMap are available in a number of formats. A GeoJSON track line is created for display in the web client. A shapefile, a netCDF file, and a Hierarchical Data Format 5 (HDF5) file are produced for display and analysis in ArcGIS and other tools (figure 1.11). The output files contain the date, latitude, longitude, and depth of the particle; the temperature and salinity values at the point if they are available from the hydrodynamic model; and the u , v , and w speed components at the grid point. A log file is also produced for troubleshooting and system analysis. TopoJSON is being considered in the future to allow a web client to show the track lines for each individual particle instead of using the single centroid track line GeoJSON output format that is currently available. An experimental TopoJSON output format is available at https://github.com/kwilcox/geojson_examples/blob/master/particles/huge_particle_tracklines.topojson.

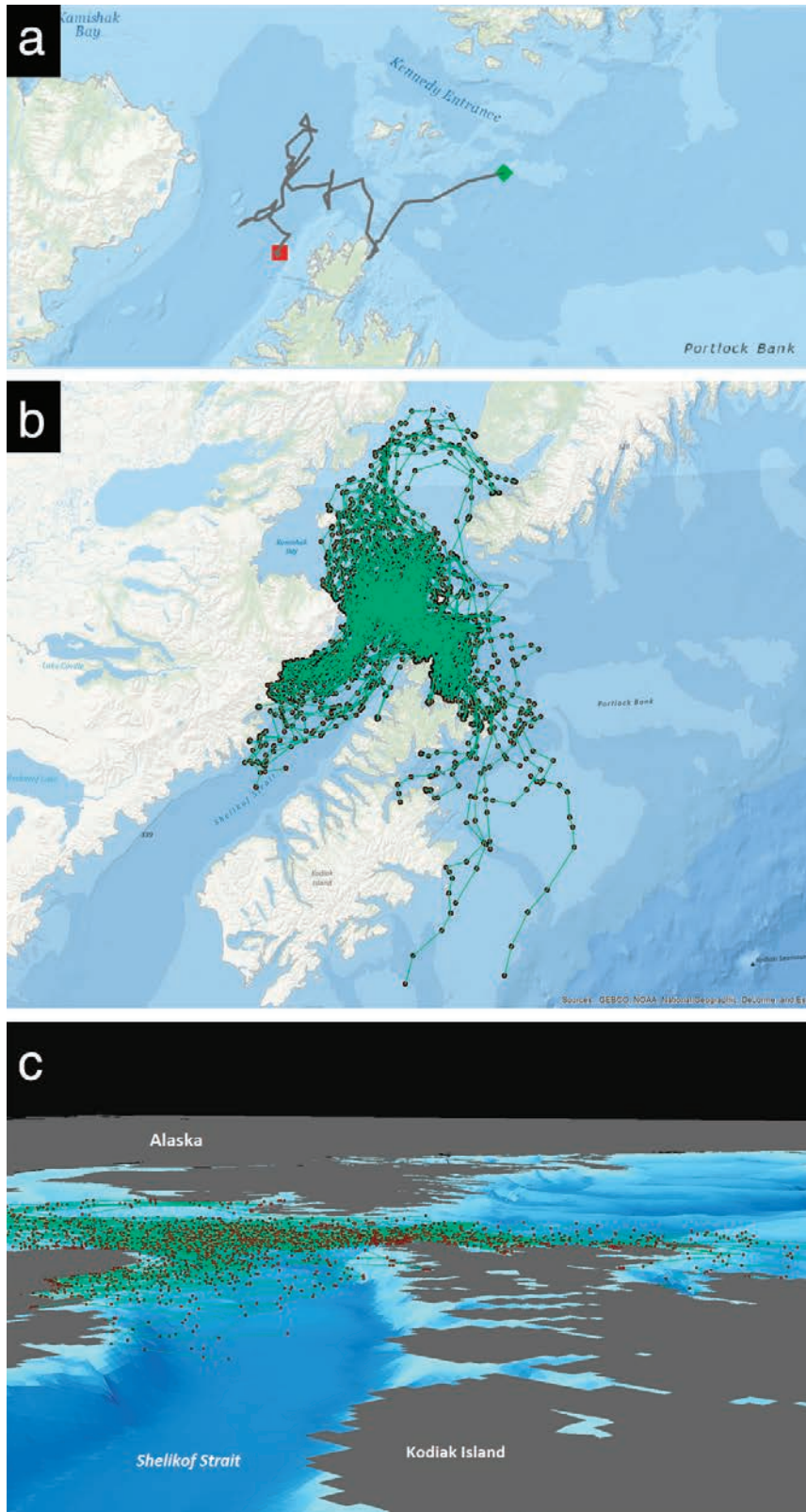


Figure 1.11. Results from a LarvaMap run shown in (a) the LarvaMap interface and the track lines shown in the (b) ArcMap and (c) ArcScene applications in ArcGIS. By NOAA Alaska Fisheries Science Center; data sources: NOAA Alaska Fisheries Science Center, Esri, DeLorme, GEBCO, NOAA NGDC, National Geographic Society, HERE, Geonames.org, and other contributors.

Post Processing and Product Generation: Gridded Products

LarvaMap contains some utilities for post-processing the netCDF output into gridded products. These utilities are typically used for stochastically representing the probability of a Lagrangian element passing through a grid cell or, in the case of larvae, settlement occurring in a grid cell based on an ensemble of model runs. The gridded products can be output as GeoTIFFs for use in GIS applications such as ArcGIS ArcMap. This workflow is not automated as part of the model implemented in the cloud, but it can be easily added to the cloud-based system.

Role of the Cloud and ArcGIS for Server, Future Needs

Creating EcoDAAT and LarvaMap has allowed us to explore practical applications of cyber-GIS advancements. Although EcoDAAT is not currently a cloud solution, the architecture of ArcGIS for Server means that the tool can be redeployed using cloud storage and computation. The web client can use a variety of back-end architectures. LarvaMap is a more classic implementation of cyber-GIS that uses cloud storage, optimized data transfer schemes, cloud-based computation, and local analysis of model results. Thus, it requires solutions to meet Yang et al.'s (2011) challenges of data intensity, computing intensity, concurrent intensity, and spatiotemporal intensity.

Implementation of these tools has produced some challenges, and some unexpected opportunities. The EcoDAAT integration of data and ability to make data easily accessible has also raised challenges concerning data sharing and data use. Although the recent White House memorandum on open data (President Barack Obama 2013) calls for free and open distribution of data, this must be balanced with the need to make sure that the data being distributed is fully quality controlled and the right of the researchers to their intellectual property is respected. Tiered access and other technical solutions supported by cyberinfrastructure will allow us to balance these needs.

Deploying LarvaMap raises challenges in procuring cloud resources for government use. Full deployment will require the security accreditation of cloud storage and computing and improved procedures for payment for cloud time. Most or all of these challenges can be solved by the creation of private clouds within the federal system or by deploying LarvaMap using local high-performance computing resources.

One totally unexpected use of LarvaMap is as a teaching tool. Because of its ease of use and computational capabilities, it can be used by students to explore larval transport. A recent biological oceanography course in the joint Massachusetts Institute of Technology–Woods Hole Oceanographic Institution graduate program had the students using the tool to create and run scenarios for their final projects (L. Mulineaux, personal communication). This usage also provided us the benefit of extended stress testing of the system as the students created and ran numerous models.

These tools have proven that “GIS detached from the desktop and deployed on the web” can provide critical resources to support fisheries research and management. We plan to continue taking advantage of future cyber-GIS developments to improve and expand our capabilities.

Acknowledgments

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Supplemental Resources

For the digital content that goes with this chapter, go to the following links or QR codes.

Hyperlinks are also available in the book's online resources (esri.com/esripress-resources/ocean-solutions-2e).

LarvaMap-Related Resources

- Larval Behavior Library to create, catalog, and share larval behaviors, at <http://behavior.larvamap.axiomdatascience.com>



- LarvaMap Transport Model written as a Python library, at <http://github.com/asascience-open/paegan-transport>



- LarvaMap web client for interacting with a web service through a REST API, at <http://services.asascience.com/mapapp/larvamap>



- Paegan Common Access Library, at <https://github.com/asascience-open/paegan>



- Online archive of particle-tracking models, at <http://www.nefsc.noaa.gov/drifter/particles.html>



- OceanNOMADS for access to hydrodynamic models, at <http://ecowatch.ncddc.noaa.gov>



- Access to high-resolution operational hydrodynamic models, at http://www.opc.ncep.noaa.gov/newNCOM/NCOM_currents.shtml



EcoDAAT-Related Resources

- Ichthyoplankton Information System for information on the early life histories of fish species in the Bering Sea and Gulf of Alaska, at <http://access.afsc.noaa.gov/ichthyo/index.php>



- Survey data on the occurrence of adult pollock and other species, at http://www.afsc.noaa.gov/RACE/groundfish/survey_data/default.htm



- Mapping essential fish habitat for a variety of species, including pollock, at <http://www.habitat.noaa.gov/protection/efh/efhmapper/index.html>



CHAPTER 2

What GIS Experts and Policy Professionals Need to Know about Using Marxan in Multiobjective Planning Processes

Heather M. Coleman and Jeff A. Ardron

Abstract

Decision support tools are increasingly becoming part of marine conservation planning, and a body of case studies and good practices is growing around their usage. Nevertheless, misconceptions persist among managers and stakeholders about what these tools can provide, and among technical experts, who question how the tools may offer an advantage in planning processes. This chapter provides a summary of these issues with a focus on challenges and problems faced in real-world marine conservation planning. The popular decision support tool Marxan, designed to inform multiobjective spatial conservation and resource-use planning decisions, provides a good example of decision support tool applications and lessons over two decades of use. Marxan helps select networks of areas that represent target amounts of features at minimal “cost.” Many challenging decisions and considerations are inherent in solving this problem, including setting targets, determining appropriate socioeconomic values, and interpreting and communicating results. In the end, however, handling relationships with stakeholders and managers in a planning process can make or break acceptance of the tool and the use of its results.

Introduction

Marine protected areas (MPAs) have become an increasingly applied tool yet remain a controversial issue in spatial resource management. In part, this is because of the lack of a systematic process and clear definition and implementation of planning criteria, as well as heavy emphasis on placement of MPAs to avoid conflict with existing human uses (Devilleers et al. 2014). However, specific elements have recently been identified to explain the success, failure, and indifference of many MPAs to biodiversity and resource enhancement (Edgar et al. 2014). Just as these common elements should aid development of effective MPA networks, recognizing themes of successful multiobjective tool use should help guide the process of meeting MPA network criteria. Although this chapter focuses largely on experiences gained through marine conservation planning, we believe that much of its content is also applicable to marine/maritime spatial planning (MSP) and multiobjective resource planning in a broader sense.

To meet a range of conservation and other planning objectives, a systematic approach has taken the place of the ad hoc, site-by-site approaches of the past that resulted in overrepresentation of certain habitats or ecosystems at the expense of others (Pressey et al. 1993; Simberloff 1998; Possingham et al. 2000). The process of systematic conservation planning (SCP) was developed to describe the location, design, and management of areas that comprehensively represent regional biodiversity and targeted resources (Margules and Pressey 2000; Margules and Sarkar 2007; Moilanen et al. 2009). A clear set of objectives, incorporation of the best available information, the inclusion of stakeholders, transparent analysis and reporting, and iterative decision-making all characterize good SCP practices. However, the full promise of SCP has remained elusive because of emerging complexities such as proper accounting of the costs associated with proposed solutions and appropriate use of available decision support tools (McDonald 2009; Ardrón et al. 2010).

The Role of Spatial Tools in a Systematic Planning Process

Decision support tools (DSTs) are designed to benefit planning processes by assisting with complicated problems that are beyond human intuition or conventional approaches. Conservation-focused DSTs are software programs that (1) guide decisions intended to promote protection of biodiversity, ecological structure and function, ecosystem services, and/or scenery; and (2) at minimum, identify either sets of complementary sites needed to achieve quantitative targets for biodiversity features or the complementary contribution that individual sites make to conservation within a region (Sarkar et al. 2006).

In recent years, DSTs that help guide ecosystem-based management, integrated ocean management, adaptive management, MSP, and SCP processes have proliferated. Many of them are free or inexpensive to use, but a commonly associated problem is a lack of dedicated maintenance and/or adequate user support, often making the tools unreliable and difficult to use (Curtice et al. 2012). In some cases, proper usage and good practices are documented (Watts et al. 2009; Ardron et al. 2010; Fulton et al. 2011; Guerry et al. 2012). However, there are few published examples that compare functions and features of these tools (cf. Sarkar et al. 2006; Coleman et al. 2011; Rozum and Carr 2013). Rarer still is discussion of how DSTs have been effectively used in the broader context of SCP or MSP processes. Many of the most informative published studies present results from multiobjective analyses and tend to feature the spatial planning tool Marxan (e.g., Chan et al. 2006; Klein, Chan, et al. 2008; Klein, Steinback, et al. 2008; Ban, Picard, et al. 2009; Christensen et al. 2009; Grantham et al. 2013). Considering the broad experience that has been built in terms of planning contexts and study locations, this chapter focuses on Marxan; however, lessons discussed here can often apply to the broader use of multiobjective planning tools in general (e.g., Zonation from Moilanen 2014, ConsNet from Ciarleglio et al. 2009, and C-Plan from Watts et al. 2014).

With more than 9,000 downloads from users in at least 140 countries over the past four years alone (M. Watts, personal communication, June 2014), Marxan has become the most popular tool of its kind. It was developed to address the “minimum-set problem” of protecting at least a set amount of conservation features for the minimum cost (McDonnell et al. 2002). Over the past 15 years, experience in implementing Marxan results has shown that part of its success comes from the ability to help practitioners adhere to the stages of SCP (box 2.1), which promotes a comprehensive, flexible, complementary, repeatable, and efficient process (Possingham et al. 2010). For example, using Marxan to plan a network of protected areas requires users to set explicit targets for species and habitat inclusion (stage 4 of the SCP process), a potentially politically charged consideration that can be too easily deferred or neglected in planning situations without tools that require this difficult, yet essential, discussion to occur (Lieberknecht et al. 2010).

Box 2.1. Stages of SCP

Systematic conservation planning can be described in 11 key stages, based on guidelines presented by Pressey and Bottrill (2009) and including feedback between stages. This set is meant to be indicative and should not be considered definitive (for example, Possingham et al. [2010] propose an eight-stage approach):

- 1. Scope and budget the planning process** to make decisions about boundaries, the planning team, budget, necessary additional funds, and how each step in the process will be addressed, if at all.
- 2. Identify and involve stakeholders** (those who will influence, be affected by, or implement actions) from the start of a planning process to encourage information exchange, enable collaborative decision-making, foster buy-in, and increase accountability. Different groups of stakeholders will need to be involved in different ways in specific stages of planning.
- 3. Describe the context for conservation areas** in terms of social, economic, and political factors. Identify the types of threats to natural features that can be mitigated by spatial planning and the broad constraints and opportunities around conservation actions.
- 4. Identify clear goals and objectives** to articulate priorities for protection and restoration/enhancement of biodiversity (e.g., representation, persistence) and socioeconomic interests (e.g., ecosystem services, livelihoods).
- 5. Collect spatially explicit data on socioeconomic variables and threats**, including human uses, tenure, extractive uses, costs of conservation, constraints and opportunities to which planners can respond, and predictions about the expansion of threatening processes.
- 6. Collect spatially explicit data on biodiversity and other natural features**, including representation (e.g., vegetation types), focal species, habitat types, biodiversity proxies, ecological processes, and ecosystem services.
- 7. Establish targets** by interpreting goals/objectives to quantitatively specify how much of each feature to protect within the network, and establish design principles to influence the geographic configuration (including size, shape, number, and connectivity of sites) of the network.
- 8. Review current achievement of objectives** and identify network gaps (often through remote data and field surveys) to determine the extent to which targets are already met.
- 9. Select new conservation areas** (often with stakeholders) from multiple location and configuration options that complement existing protected areas for cohesive networks that meet targets and design criteria. Factors that influence decisions usually include costs, constraints, and opportunities for effective conservation.
- 10. Implement conservation action** by making decisions on fine-scale boundaries, appropriate management measures, institutional arrangements, implementation sequencing priority, and other site-specific considerations to ensure that selected areas are given the most feasible and appropriate management and that areas are prioritized for action when resources are limited.
- 11. Maintain and monitor** the protected area network to evaluate whether management is effectively preserving ecological integrity and long-term persistence in the context of original goals and objectives.

Strengths and Limitations in the Use of Decision Support Tools such as Marxan

When used correctly, planning tools such as Marxan and its expansion, Marxan with Zones, save users time and resources, act as a guide for moving from data to decision-making, build on past work rather than repeating it, reduce the need for human expertise, help explore a wider range of alternatives and trade-offs, document decisions about inputs and parameters, and help integrate planning across diverse sectors (Curtice et al. 2012; Possingham et al. 2010). However, these benefits cannot be realized if DSTs are used without the proper data, as detailed in the following.

The use of tools such as Marxan is seldom a quick process, and we caution that it comes with an initially steep learning curve. Furthermore, using Marxan is not recommended in regions where data is inconsistent (patchy) and/or scarce, as the tool will simply highlight the few areas that contain the most data, and cannot take into consideration features for which there is no data. This uneven and/or inadequate coverage of a planning region may miss important ecological features or socioeconomic information that could dramatically influence site selection results. In such cases, it can be beneficial to incorporate facilitated and structured discussion, which for “simpler problems” (i.e., those with few data layers and associated targets and costs) can often lead to similar results with less time and technical effort (Ban, Hansen, et al., 2009; Ardron et al. 2014). In such situations, if planners decide to also use a DST, the tool should play a secondary role in the decision-making process.

In many data-poor situations, it is possible to address some deficiencies, especially at coarse scales, using surrogates. For example, if species occurrence data is unavailable, climate profiles and other environmental parameters may be appropriate surrogates for developing predictive habitat models. Models can be updated or later replaced in the analysis if and when more data becomes available (e.g., Sarkar et al. 2005). Likewise, socioeconomic information such as fishing effort can be approximated by data that is more easily collected, such as boat counts (Weeks et al. 2010). Also, surrogates such as sea surface temperature variation can be used to inform the selection of suitable future habitat to protect a range of management options that account for climate change (Makino et al. 2014).

In general, more data is often available than may be first thought. Various institutions often hold a number of different datasets that describe an area at global, regional, and national scales. Taking stock of these various data sources is one of the first and often most time-consuming tasks in SCP, and is necessary regardless of whether a DST is ultimately used or not.

How Marxan Can Fit into a Systematic Planning Process

Marxan is freely available, spatially explicit software hosted by the University of Queensland, Australia, to support spatial planning. Commonly, practitioners use Marxan analyses to protect at least a certain percentage (termed a *target*) of each representative habitat type, endangered species, climatic zone, and so forth (the *features* of an analysis). The site selection process involves (1) collecting planning units that contain at least the targeted amount of features, while (2) minimizing the sum of selected area perimeters, and (3) avoiding socioeconomically important areas (termed *costs*, for which high values make a planning unit less efficient to include) where possible. Marxan allows flexibility in aspects of an analysis such as the number and types of features included, the target that is set (or not set) for each feature, whether any planning units have a preexisting status (e.g., necessarily included or excluded from all network configurations), and the

cost of including each planning unit in the reserve network. Variable emphasis can also be placed on the importance of meeting specific targets and on clumping sites together versus creating a dispersed network (more information available in Ardron et al. 2010). For example, figure 2.1 shows the powerful effect that calibration can have on results through the boundary length modifier (BLM) setting (PacMARA 2012).

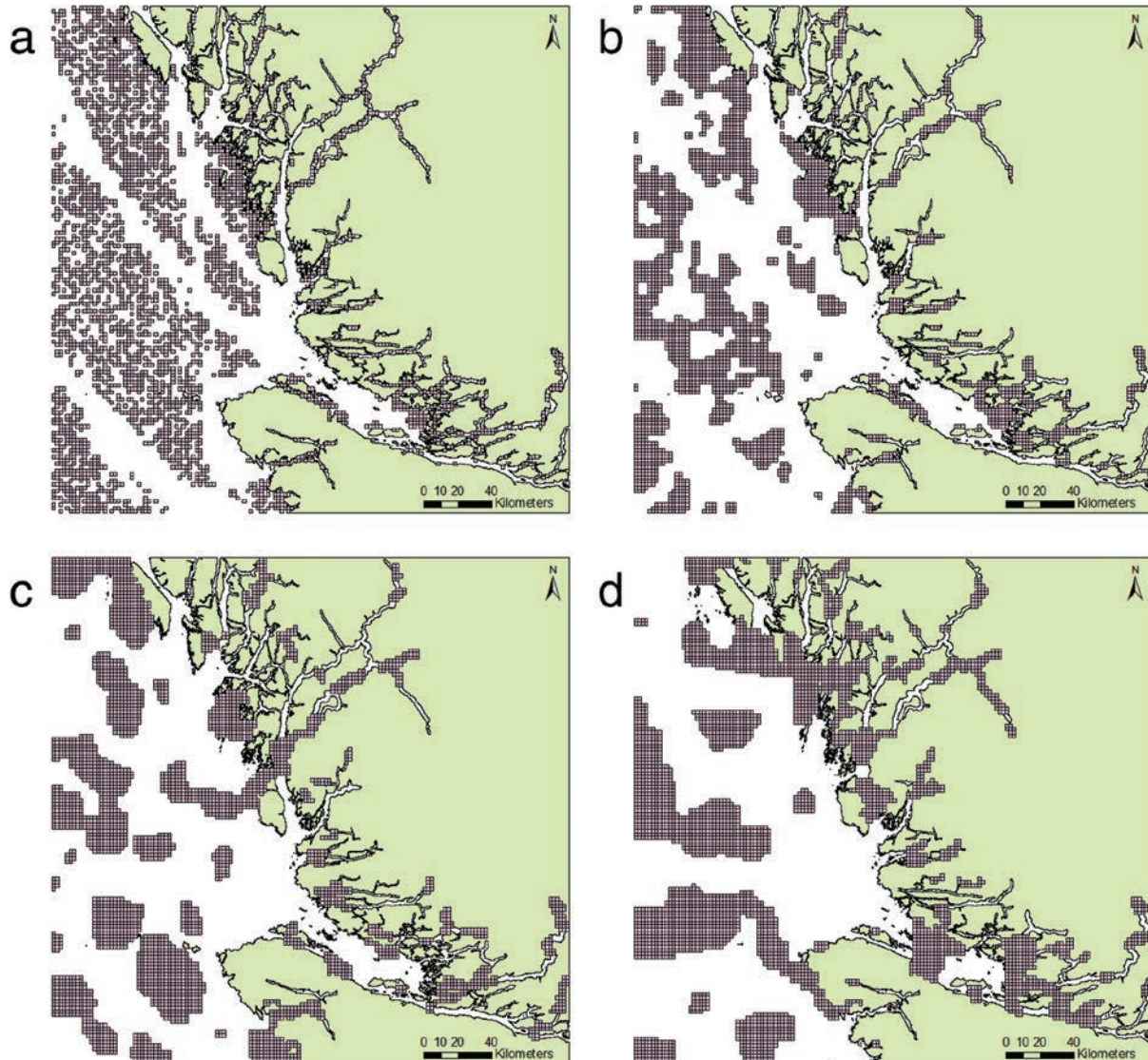


Figure 2.1. Results of a demonstration Marxan analysis used for Pacific Marine Analysis and Research Association training courses that describes hypothetical planning along the central coast of British Columbia, Canada. Purple shading indicates areas selected as part of a complementary network for each scenario. With all other parameters held constant, (a) shows no weighting of boundary length (BLM = 0); while (b), (c), and (d) show increasingly strong influence of total boundary length minimization (BLM = 0.1, 1, and 10, respectively) on network configuration. Data source: British Columbia Marine Conservation Analysis Project Team. 2011. *Marine Atlas of Pacific Canada: A Product of the British Columbia Marine Conservation Analysis*. Available at www.bcmca.ca.

Although initially conceived in the context of marine conservation planning, Marxan is also applicable to freshwater, terrestrial, or a combination of systems (Tallis et al. 2008; Ball et al. 2009; Beger et al. 2010; Hazlitt et al. 2010; Makino, Beger, et al. 2013; Klein, Jupiter, and Possingham 2014; Klein, Jupiter, Watts, et al. 2014). Marxan has also been used in a variety of ways other than developing recommendations for new conservation sites (for example, considering existing networks [Stewart et al. 2003; Fuller et al. 2010], examining the efficiency of ad hoc planning processes [Klein, Chan, et al. 2008; Mills et al. 2012], and planning for persistence in the face of climatic change [Game et al. 2008; Makino et al. 2014]). Other examples of innovative Marxan uses include optimizing a measure of ecosystem services in addition to biodiversity (Chan et al. 2006; Luck et al. 2012); prioritizing a network of fishing sites to maintain viability of the industry (Ban and Vincent 2009); and using conservation priority as the cost for industrial site selection, and vice versa, to inform potential conflict analysis (PacMARA 2012).

In perhaps the best-known case worldwide of MPA creation involving Marxan (e.g., Ecology Centre of the University of Queensland 2009), the Australian government cosponsored an analysis using stakeholder engagement to inform protected area designation in the Great Barrier Reef (GBR). Substantial stakeholder involvement in planning promoted impartiality in the recommendations that Marxan returned, and the resulting maps comprised an effective platform for communication and compromise when used iteratively to zone the GBR (Lewis et al. 2003; Davis 2004; Pattison et al. 2004). However, by systematically avoiding areas of high human “cost,” the GBR zoning plan has recently come under criticism (Devillers et al. 2014). This emerging controversy highlights the tendency of DSTs to simply “do as they are told,” and stresses the need to address larger questions over the objectives and trade-offs that arise in planning processes.

Marxan with Zones has since been developed to more efficiently allocate zones to meet multiple objectives and has been used to inform planning in many regions globally (e.g., Makino, Klein, et al. 2013). Marxan with Zones is based on the same software as Marxan (akin to layers of Marxan nested within one another) but benefits from the use of more data (i.e., zone-specific datasets) to operate at its full potential. Creating Marxan with Zones scenarios also involves more variables to control and requires more explicit judgments, which complicates usage but allows more flexibility and range of options than using Marxan alone. The contribution of zones to different targets, the costs of implementing different zones in different locations, and the interactions between zones are all considered with this advanced tool (Watts et al. 2009). Marxan with Zones makes it possible to create a range of conservation schemes, from “no-take” to allowing only certain types of extractive activities, depending on the designation (Klein et al. 2009).

Both programs help users evaluate how well each scenario meets conservation and socioeconomic objectives, thereby facilitating the exploration of trade-offs. However, Marxan with Zones has the distinct advantage of allowing what would be treated as *cost layers* in Marxan (e.g., a specific fishery) to be separate features within the analysis, with specific targets set for each associated zone (e.g., multiple use, specific industry access, indigenous access). This functionality allows users to avoid a major shortcoming of Marxan, which is requiring that all cost data be combined into a single value for each planning unit. However, the greater power of Marxan with Zones leads to fundamental questions regarding the efficacy of different management treatments (e.g., differing levels of restrictions) in different zones, or *zone effectiveness* (Makino, Klein, et al. 2013), and their effects on biodiversity, which can be difficult to predict.

Lessons Learned

Further recommendations on the use of Marxan, including the topics briefly mentioned in this section, are covered in detail in the *Marxan Good Practices Handbook* (Ardron et al. 2010), as well as in two workshop reports on the topic (PacMARA 2008; BCMCA and PacMARA 2010). Following, we expand upon considerations that have emerged as central in the course of technical and managerial DST trainings through our involvement in the Pacific Marine Analysis and Research Association (PacMARA). PacMARA is a charitable organization based in British Columbia, Canada, that is dedicated to building capacity in marine and coastal planning internationally. The organization provides facilitation, training, analysis, and support for the ocean planning community, both within and external to planning processes, through workshops, courses, symposia, and spatial planning research case studies. In addition to our own work, we have learned a great deal from participants while leading hands-on and conceptual capacity-building courses throughout the world (PacMARA has held 40-plus courses and workshops for 800-plus participants from 50-plus countries).

In the following sections, we focus on insights that we believe to be relevant to practitioners who want to understand how spatial tools and their outputs fit into the larger context of systematic planning. These are, for the most part, personal observations; however, although many of these “tips” are Marxan-specific and unpublished, they are often similar to good practices that have been highlighted in the marine planning and GIS literature more generally (e.g., Mitchell 2001; Ehler and Douvere 2009). In addition, there are good practices in cartography and the display of quantitative information that deserve close attention; however, these practices are amply covered in the existing literature (e.g., Monmonier 1996; Tufte 2001) and are not addressed further here.

Asking the Right Question

For a spatial planning tool to appropriately prioritize areas for protection, practitioners must be cautious to ensure that they are asking the right question of the tool. Game et al. (2013) elaborate on this issue with several valuable insights, and here we highlight a few practical considerations. Marxan and Marxan with Zones can be used in a seemingly endless variety of ways (Watts et al. 2009; Martin et al. 2010); however, the value of their outputs will depend in large part on whether they address the legal and policy requirements of a particular audience and planning process. For example, although displaying the results of an MPA network that protects 20% of a region can have heuristic value, the usefulness of implementing such a network will be limited if governing bodies are interested in meeting only lesser targets (e.g., the Convention on Biological Diversity [CBD] Aichi Target 11 of 10%) (CBD 2011). Likewise, study areas that mismatch or fall outside the jurisdiction of a given planning process, even if they make more “ecological sense,” will have little value in terms of the planning process’s mandate.

Common Misconceptions

The original and rewritten Marxan manuals explain the algorithm and its objective function (Ball and Possingham 2000; Game and Grantham 2008). However, the explanation is necessarily technical with some mathematical notation.

Marxan Is a ‘Black Box’

The black-box argument often arises when stakeholders are wary of a planning process, and hence, any analyses associated with it. In our view, this is not about understanding the math, simulated annealing, or other aspects of Marxan’s objective function; rather, it is mostly a question of building trust. If stakeholders are given an overview of what Marxan does, and can see that their inputs are incorporated and actually affect Marxan’s outputs, a great deal of the mistrust dissipates, and concerns about how Marxan works are minimized.

Marxan Is a Model

Marxan is, in fact, an optimization algorithm. However, this technical difference is often lost on a nontechnical audience. For a politician, the term *model* can indicate that the results are not real, and based largely on assumptions, seemingly making them therefore not applicable. There is probably no easy way to completely correct this misperception; however, emphasizing that Marxan simply suggests a number of good solutions based on user-defined planning targets can steer discussion away from notions that it constructs artificial realities or otherwise “knows” things about the system.

The ‘Best Solution’ Is the Ultimate Planning Answer

Marxan terminology does not always translate readily into planning process discussions, and the term *best solution* is a case in point: it is only meant to indicate the solution with the best overall score (which is based to a large degree on the efficiency of the network). However, identifying the lowest score in no way suggests that the other favorable, but slightly less efficient, solutions are not worthy of consideration. Indeed, considering that one of the great advantages of the tool is its ability to produce a variety of good solutions, it would be counterproductive to limit discussion to just one. Additionally, many other considerations that are not (or cannot) be quantified into data layers will affect planning choices. Marxan’s solutions should be seen as suggested starting points and topics for discussion and engagement rather than end points.

Selection Frequency Is the Same as Ecological Irreplaceability

Selection frequency vis-à-vis ecological irreplaceability is another unfortunate misunderstanding of terminology that arose because of the use of the word *irreplaceability* in an early version of the Marxan manual, which then crept into the early Marxan literature. How often a given area is selected in Marxan solutions can be a good indication of how “useful” it is in a variety of scenarios (Ardron 2008). However, this repetition of selection may or may not mean that it is irreplaceable (Fischer et al. 2010). This misunderstanding is discussed in more detail in the *Marxan Good Practices Handbook* (Wilson et al. 2010), but we have listed it here because misuse of the term irreplaceability is still pervasive.

Marxan Is Only Used for Identifying Marine Protected Areas

Although recommending MPA network locations has been a common application of the Marxan tool, it is also frequently used in terrestrial and freshwater settings. In any case, Marxan can also be used to identify areas for extractive or other types of uses beyond conservation (e.g., Ban and Vincent 2009), as nothing about the tool inherently predisposes it to MPA site selection.

Including Socioeconomic Considerations Detracts from a ‘Pure’ Ecological Analysis

The misconception over including socioeconomic considerations is based on the legitimate fear that these considerations can often dilute or trade off conservation values in planning processes. However, in the case of a Marxan analysis, adding socioeconomic interests adds relevant constraints and increases the practicality of solutions, among other benefits (Ban and Klein 2009). If some ecological targets are no longer being met after the addition of human use or interest data, Marxan parameters can be adjusted until they are again being met, according to procedures described in Game and Grantham (2008).

Various ‘Costs’ Can Be Added Together

A shortcoming of Marxan is that it has just one cost function; and hence, constraints that are measured differently (e.g., the values of various fisheries as well as other human activities) will have to be reconciled. Various strategies exist for dealing with this issue (Ban and Klein 2009) (for example, translating the different constraints into a common *currency*, such as dollars or jobs). However, adding different measures together as though they were the same, like “apples and oranges,” is inappropriate (Cameron et al. 2010). Although Marxan with Zones, unlike Marxan, allows for the inclusion of multiple cost layers, the costs are simply added internally; and so the issue still largely remains (Watts et al. 2009). Although this inclusion has led to a further misconception that the problem has been solved, using Marxan with Zones can indeed alleviate the issue of multiple costs if some of the costs are available as input layers and can be associated with zoning targets. (Costs are discussed again later in this chapter in the context of stakeholder relations.)

A Marxan Analysis Can Be Completed in the Time It Takes to Learn How to Use the Tool

Grossly underestimating the time required for a Marxan analysis is perhaps the most common misconception of all (e.g., a typically expected time frame might be a few weeks or perhaps a few months). However, this misconception has a grain of truth: learning Marxan should not take more than a few weeks, and less time if one takes a course. What consumes the months (and often years) of an analysis is mostly data related: acquisition, preparation, quality assurance, collation into single layers, and finally conversion into input files (Martin et al. 2010). Another often significant drain on time in an inclusive process is securing stakeholder and/or scientific agreement on targets (BCMCA and PacMARA 2010; Ban et al. 2013).

Working with Stakeholders and Their Information

One of the most challenging components of conservation planning processes is working with a diverse range of stakeholders. In the authors’ experiences, most conflicts in conservation planning processes stem from stakeholder engagement, especially concerning socioeconomic issues. The acceptance of such tools as Marxan hinge to a large degree on general stakeholder acceptance of a planning process. Cultural context is critical in this regard, as the levels of engagement and power expected from resource users, indigenous groups, industry associations, nongovernmental organizations (NGOs), and the like depend largely on the historical and cultural context of where a process takes place. For example, stakeholders in Germany have, to date, been minimally engaged in marine planning (Von Nordheim et al. 2006) and arguably expect less than those in the United Kingdom, which has seen much greater engagement (e.g., Lieberknecht et al. 2013). Further, stakeholder expectations can vary greatly across different groups (Maguire et al. 2011).

Being clear from the beginning of a process regarding the scope of planning, mandate(s), goals and objectives, what is and is not “on the table” for discussion, process limitations, and how stakeholders can expect to be engaged can avoid misunderstandings and mismatched expectations as progress is made. If stakeholders arrive later in a process timeline, it will likely be necessary to revisit some of the basics, including the agreed-on terms of reference, and again outline the benefits of participation. As the appropriate level of inclusivity can be time consuming, it is clearly preferable to involve all the necessary stakeholders from the get-go (Ban et al. 2013).

Incorporation of human-use data and values into Marxan analyses has substantially evolved over the tool’s history, from largely nonexistent (e.g., cost simply as an area of selected planning units) to use of a single measure to more integrated options such as combined costs, measures of naturalness, cumulative impacts, and habitat suitability (Ban and Klein 2009). Classifying, mapping, and integrating human uses and values, including economically and culturally outstanding areas, into DSTs helps keep the process systematic by representing ecological and socioeconomic contributions as partners in the prioritization of conservation sites. However, such data characterizations are imperfect and still require robust stakeholder discussion to examine nuances and corrections.

Marxan is limited in a number of cost assumptions, including that cost values are uniform through time and that human activities affect all features similarly. Practitioners should be sensitive to the fact that stakeholders may adamantly oppose the combination of socioeconomic datasets in an analysis, which leaves the option of running separate Marxan scenarios for each cost, or potentially using the more sophisticated (but more complicated) Marxan with Zones instead (e.g., BCMCA and PacMARA 2010). Whereas including costs in an analysis is usually complicated, it has become good practice to use more than the simple area of selected planning units (e.g., Ban, Picard, et al. 2009). Figure 2.2 shows the influence that different cost inputs can have on Marxan site selection results.

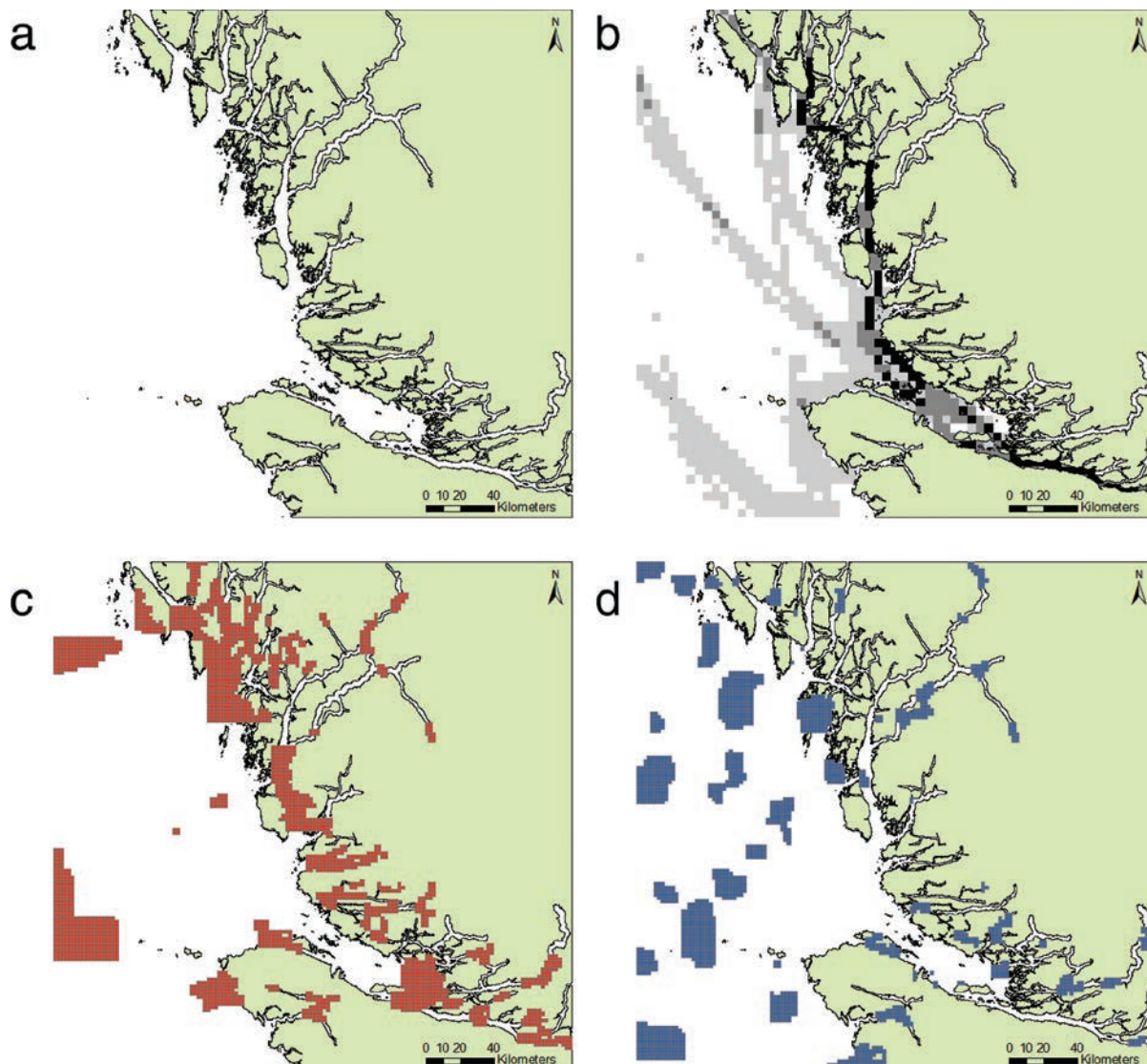


Figure 2.2. Marxan site selection results as a function of different costs with all other parameters held constant: (a) area only as cost (i.e., all planning units have a uniform value); (b) vessel density shown as the cost layer (in which darker planning units were more frequently selected); (c) selection results that consider area only as cost (red planning units); and (d) selection results that consider vessel density as cost (blue planning units) in an example used for Pacific Marine Analysis and Research Association training courses that describe hypothetical planning along the central coast of British Columbia, Canada.

Data source: British Columbia Marine Conservation Analysis Project Team. 2011. *Marine Atlas of Pacific Canada: A Product of the British Columbia Marine Conservation Analysis*. Available at www.bcmca.ca.

The key to understanding the incorporation of socioeconomic data into a Marxan analysis is recognizing that whenever multiple human uses are combined, Marxan cannot provide equity among those uses. As discussed, adding together radically different costs, such as social values (e.g., spiritual, history, identity) and economic information (e.g., profits, jobs), should be avoided.

A strategy for successfully engaging stakeholders in DST use is to initially keep an analysis simple, and then add complexity iteratively as the discussion progresses (for example, when new data is available, when new stakeholders join the process, and/or when results are reviewed and returned to the project team [BCMCA and PacMARA 2010]). Reiteration of analyses, the interactive

involvement of stakeholders (e.g., through the use of interactive tools such as *Zonae Cogito* [Segan et al. 2011; Ecology Centre of the University of Queensland 2012] or *SeaSketch* [McClintock 2012]), and the openness of practitioners to creative uses of Marxan and criticism that can improve previous analyses should all help stakeholders and decision-makers view the systematic process as legitimate.

Also, initial simplicity helps analysts assess whether the program is working correctly and whether core datasets appear to be accurate, even if first results are unrealistic (with the caveat that future iterations contain sufficient data to provide meaningful and balanced solutions). Using a range of feature targets (and potentially also clumping together factors, penalties, and costs) emphasizes the flexibility of Marxan and its solutions, as well as that of the process itself. Communicating initial and midterm outputs and soliciting feedback may be as important to building stakeholder relationships, and hence to the planning process, as the actual Marxan results themselves (BCMCA and PacMARA 2010).

Ultimately, successful stakeholder engagement in SCP depends more on a clear understanding of the context and trust in the planning process than the specifics of the tool being used. However, it is still important that participants hear an explanation of why Marxan is being used. Common benefits include (1) the tool's ability to explore more potential solutions than is possible manually, (2) finding unforeseen good solutions, (3) comprehensively including stakeholder uses and values, and (4) helping systematically explore and potentially dissolve controversy through trade-off options. Marxan also provides a transparent framework in which stakeholders can trust that their data is being considered alongside ecological information, which often supports the success of postreserve implementation. However, it is also important to temper expectations for DSTs to address contentious issues and resolve conflicts. In reality, Marxan can help users change the focus to exploring trade-offs and informing conflict, but it cannot resolve differences in values or world views (PacMARA 2008).

Presentation and Interpretation of Results

For each set of targets and costs specified (known as a *scenario*), each run of Marxan produces a different solution (e.g., figure 2.3a–b), providing a shapefile of the solution and summary tables that indicate how well each run meets the targets and its overall score. The score in Marxan is a sum of the perimeters of each set of planning units included in the solution, the cost of each unit included, and the penalty for missing any targets that were specified in the solution. Planning unit configurations with lower scores are considered more favorable. To obtain an accurate overall picture of the intended solution space, several runs (preferably, 100 or more) are recommended for each scenario. With multiple runs, the software produces a selection frequency output (e.g., figure 2.3c–d) that overlays all solutions to indicate which planning units are chosen most often. These compiled, or *summed*, solutions can highlight place selections that frequently recur, thereby suggesting that these places are likely to be important under a variety of planning scenarios.

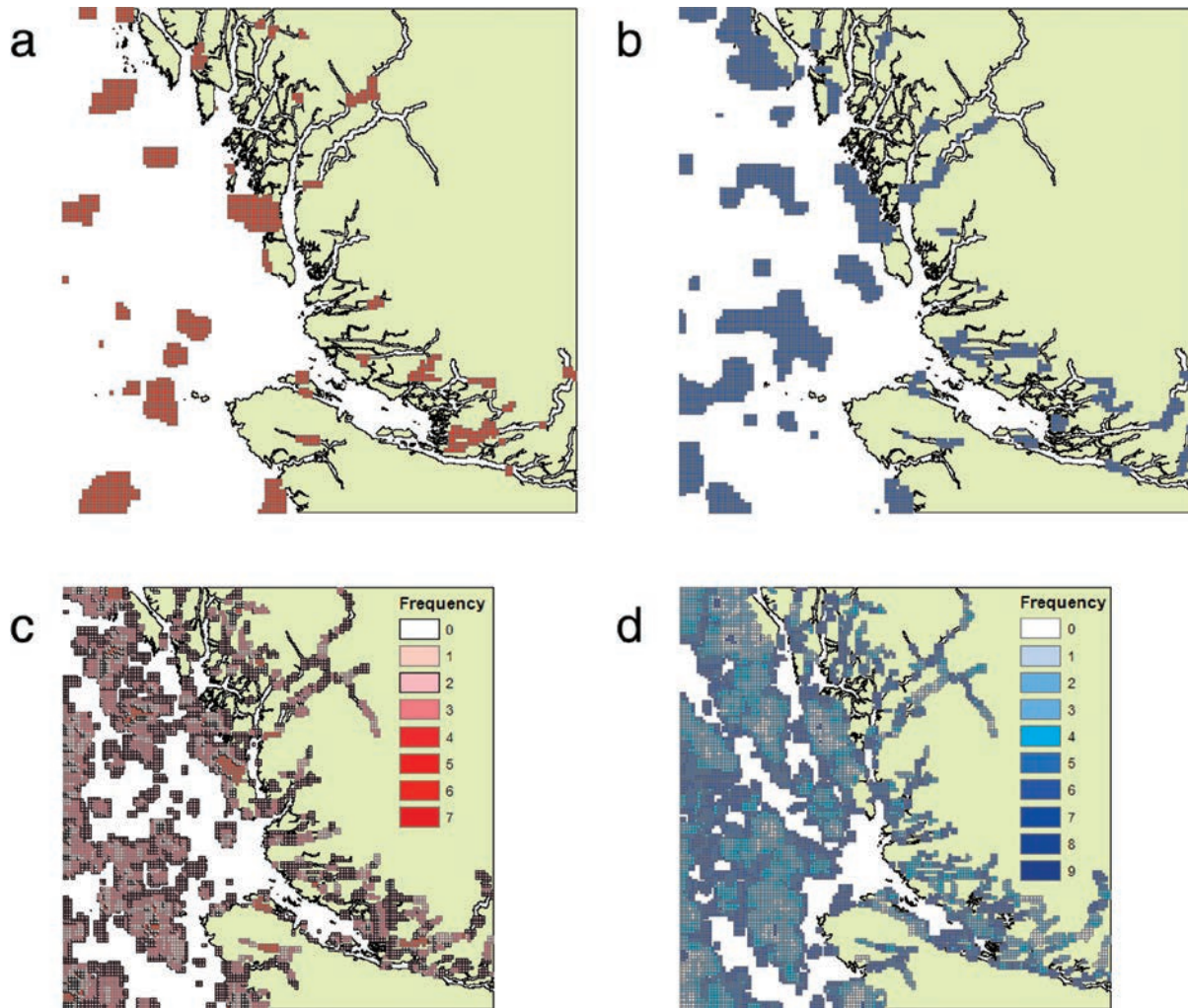


Figure 2.3. The best solutions resulting from an analysis with (a) red planning units, targets of 10%; (b) blue planning units, targets of 20%; the corresponding selection frequencies for (c), in which darker red indicates more frequent selection, targets of 10%; and (d), in which darker blue indicates more frequent selection, targets of 20%. All as used for Pacific Marine Analysis and Research Association training courses that describe hypothetical planning along the central coast of British Columbia, Canada. Data source: British Columbia Marine Conservation Analysis Project Team. 2011. *Marine Atlas of Pacific Canada: A Product of the British Columbia Marine Conservation Analysis*. Available at www.bcmca.ca.

Maps of *selection frequency/summed solution* (the two terms have the same meaning) are often appropriate in discussions with planners and stakeholders because they identify areas that are chosen most often in the analysis according to a range of targets, costs, penalties, and so forth. Selection frequency maps should be accompanied by the maps of two or three different good solutions to show possible spatial configurations that meet parameters and conditions of the analysis (e.g., figure 2.4). This practice helps avoid an audience confusing selection frequency with a network of complementary sites that combine to meet feature targets. It can be helpful to use cluster analysis to highlight the range of solutions available (Airame 2005; Fischer et al. 2010).

Effectively presenting the outputs of a Marxan analysis can be a substantial challenge to technical teams that may lack the nonbias that is necessary to communicate with stakeholders who are unfamiliar with software tools. For example, economic activities such as fisheries are typically treated as “costs” in the Marxan lexicon (but see Ban and Vincent 2009). However, stakeholders may object to such terminology as not reflecting their true economic and social values. Replacing the word *cost* with *value* when communicating Marxan results can greatly ease such communication potholes (BCMCA and PacMARA 2010).

Arranging for a third party that is skilled in communication to present results can be beneficial in encouraging focus on the key messages and avoiding distracting details that may not be relevant to the audience. This communication strategy applies to public presentations as well as internal, in which it is important for senior management to appreciate, in general terms, the value and limitations of Marxan results as they relate to the agency mandate. Ensuring the presence of competent technical personnel is always good practice to confirm that results are being interpreted correctly, and to answer detailed questions that may arise.

In general, starting communication with project team members and stakeholders early in the process can help avoid problems later. Presenting midterm results can allow for the early identification of errors and omissions. That said, practitioners are advised to be prudent about sharing initial and midterm results with groups in which trust may be an issue. Maps can easily be misinterpreted and spread beyond the meeting room without accompanying explanations and caveats. Therefore, it can be advisable to select a subset of “friendly” partners and stakeholders with whom to preview early results, and use projected images rather than paper maps.

As with all technical work, it is also good practice to avoid jargon, and limit the technical details to ones that are necessary for describing an analysis in its broadest terms. Focusing on key messages means narrowing the results that are presented, even if many more scenarios were actually completed. At the same time, showing multiple options for any one scenario reinforces the message that there is flexibility in the number of good solutions to a planning problem (see figure 2.4). This practice also helps reinforce to stakeholders that the role of an analyst is to provide results that inform decisions, not to make the planning decisions themselves.

Presenting visual results that clearly show how stakeholder values and concerns have been accounted for will speak more loudly than any number of theoretical discussions on the process of simulated annealing (McClintock 2012) and other technical details. However, stakeholders and other planning process participants should clearly understand what Marxan is designed to do: illustrate multiple options of spatially protecting targeted features for the least cost.

Anticipating conflicts and presenting them up front, either through a conflict analysis applied to Marxan results (e.g., comparing competing cost scenarios) or simply by listing issues that emerge through dialog with critics, will help dispel the misunderstanding that planning tools circumvent public dialog. Rather, the emphasis should be on the use of planning tools as a conflict resolution or minimization tool. That some conflicts cannot be resolved through the use of Marxan (or similar tools) should be acknowledged and will help keep discussions realistic in expectations of what the tool can achieve. All messages should ultimately relate back to the agreed-on objectives of the process and how the software helps address these objectives.

Discussion

We suggest that a multiobjective planning process should consist of merging many of the successful elements of ecosystem-based management, integrated ocean management, adaptive management, MSP, and SCP (Ardron 2010). Such approaches demonstrate the benefit of stating process objectives explicitly, recognizing that weaknesses in an analysis often stem from issues in the problem development stage. Not only does this practice facilitate decision-making within Marxan, such as setting appropriate targets, but it also helps illustrate the policy, political, and social framework within which conservation and resource management decisions are made.

Parties involved in a comprehensive spatial planning process can learn from systematic planning experiences about the need to bound the scope of analysis, specifically around what the pertinent legislation can and cannot do (e.g., Kirlin et al. 2013). Although the final implemented result often differs significantly from Marxan outputs, practitioners nonetheless should emphasize the value of the tool in reaching agreement (e.g., Horsman et al. 2011). Additionally, the inclusive multiobjective nature of systematic tools can help avoid “end runs,” in which a party negotiates bilaterally with a regulator outside the process (PacMARA 2008).

Although conservation planning DSTs have advanced considerably in recent years, there is still room for growth and improvement. For example, persistent challenges faced in marine spatial and systematic conservation planning include (1) the significant data requirements for many tools that are unfulfilled because of missing or poor-quality information; (2) stakeholder isolation because of the complexity of optimization tools; (3) overwhelmed managers and planners, stemming from the quantity and/or lack of straightforward interoperability of available DSTs; (4) availability of capacity building and training for managers; and (5) the lack of ground-truthing of optimal model outputs (McClintock et al. 2013).

Conclusion

The appropriate role for Marxan, as with other DSTs, is to support decision-making. These tools can suggest efficient sets of areas for conservation or other types of management. However, they will not provide final answers or solve difficult value-laden decision-making. Using planning tools does not diminish the importance of human input and collaboration nor the need to manage prejudice, politics, territory, mistrust, or technophobia. DST-generated options must inevitably be revised to yield a final plan that considers the full range of political, socioeconomic, and practical factors.

Although the use of Marxan as a DST can facilitate stakeholder engagement, and encourage a systematic approach, it is far from a guarantee of fruitful participation and acceptance of the planning process. For that outcome, building trust through political and social channels is necessary. Practitioners must be ready to cautiously interpret, to both their colleagues and superiors and to the public, factors such as outputs in the context of data limitations, the parameters used, functioning of the tool itself, and how all these pieces relate to the objectives of the planning process. Nevertheless, the appropriate use of DSTs can provide an effective, efficient, and viable means for linking science with policy, while negotiating the minefield of legal, scientific, and stakeholder requirements, and thereby lead to policy options that are otherwise unlikely to be identified.

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CHAPTER 3^{Updated}

Artificial Reefs, Beach Restoration, and Sea Turtle Nesting in Martin County, Florida

Alexandra Carvalho, Kathy Fitzpatrick, Jessica Garland, and Frank Veldhuis

Abstract

The Martin County Coastal Engineering Division manages several programs, including habitat management and restoration (inshore and offshore artificial reefs, oyster restoration, and natural reefs), beach management, Saint Lucie Inlet maintenance, waterway improvements and dredging, anchoring and mooring sites, and a few countywide coastal monitoring projects that focus on the coastal ecosystem, topographic and hydrographic data collection, and rectified aerial photography.

To consolidate and manage the large volumes of information created by the permitting process for each coastal project, and to facilitate the access to historical and current project data, the Coastal Engineering Division opted, in 2003, to consolidate its coastal data into a GIS. The system now provides access to over 20 years' worth of coastal project data that is either in a GIS or stored elsewhere but linked to a GIS. It also provides several tools to retrieve and share data. Users refer to the consolidated information and tools as the county Coastal GIS program.

This chapter briefly describes the history of the Coastal GIS program, its goals and objectives, the data consolidation and organization strategy, the data model and geodatabase schema, types of GIS apps developed, and examples of applications for improved project management and planning of future projects.

This chapter also describes two of the most active coastal programs: the artificial reefs program and the Hutchinson Island Shore Protection Project. The Coastal Engineering Division deploys new artificial reefs annually and monitors existing and new reefs frequently after construction. The project at Hutchinson Island, an example of the county's beach program, illustrates the importance of beach restoration to coastal communities.

Each case study provides a brief overview of projects that each program encompasses, the types of spatial data they produce, and how the Coastal GIS program team organizes these datasets. The chapter concludes with a description of GIS program tools developed to help with project management and the data-sharing needs of the Coastal Engineering Division as well as concepts for future tool development.

Introduction

Martin County, Florida

Located on the east-central coast of Florida, Martin County covers 556 sq mi and supports a population of approximately 150,000 residents. With only four municipalities, this low-density county (approximately 270 residents per square mile) sits in sharp contrast to the highly developed counties to the north and south. The Atlantic Ocean and Lake Okeechobee bound the east- and west-county shorelines, respectively. The Okeechobee Waterway, one of two federal waterways within county boundaries, connects the two water bodies. A second waterway, the Florida Intracoastal Waterway, runs the length of the state along the Indian River Lagoon in Martin County.

Water—its quality and access to it—defines the unique lifestyle and economy of Martin County. The Saint Lucie Inlet, sitting at the confluence of the Florida Intracoastal Waterway, Okeechobee Waterway, and Atlantic Ocean, provides important services to boats navigating to destinations toward the north and south of the state and between the Atlantic Ocean and Gulf of Mexico (east–west). It also serves as a popular departure site for trips to the Bahamas.

Lake Okeechobee sits at the northern extent of North America’s largest wetland system, the Everglades, a location included in federally mandated restoration activities. The county mainland includes extensive natural uplands, wetlands, and sections of two barrier islands separated by Saint Lucie Inlet. Federally protected estuaries separate the county mainland and barrier islands.

These estuaries, linked to the Atlantic Ocean through Saint Lucie Inlet, are important habitat for commercially and recreationally important fisheries as well as for several threatened or endangered species such as the West Indian manatee and smalltooth sawfish. The beach/nearshore area also supports threatened and endangered species such as loggerhead, green, and leatherback sea turtles; wading birds (e.g., great blue heron and wood stork); and migratory wintering birds (e.g., piping plover). Martin County also sits at the northern extent of the Florida (Coral) Reef Tract.

Martin County considers environmental preservation and restoration its top priorities. This focus has allowed the county to purchase and hold in preservation large tracts of land. Restoration and habitat creation projects, typically focused on the freshwater/estuarine/marine habitat continuum, receive strong support from county taxpayers. For this reason, increased public awareness and information sharing is critical to keeping the public engaged and interested.

Coastal GIS Program Overview

The Martin County Coastal GIS program started in 2003 with a vision of a fully integrated, GIS-based coastal information system designed to provide coastal managers, planners, and the public easy access to coastal information (Carvalho et al. 2003).

Goals and Objectives

Since its inception, the goals of the program have been to

- facilitate coastal engineering project planning and management,
- consolidate and manage permit and grant information held by multiple contractors and agencies,
- track monitoring and compliance requirements for each permit and grant, and

- reduce the staff time spent gathering information for public records and public requests for information (RFIs).

Accomplishing these goals is a continuous process that involves consolidating and organizing the county's coastal data, developing the tools to provide the county and public with easy access to coastal project information, and streamlining contractors' coastal data submissions.

Program History and Current Status

During 2003 and 2005, the county made several efforts to develop a geodatabase schema and data access. Decreased funding reduced the program to a series of coastal program data consolidation efforts in 2007, 2010, 2012, and 2013. In 2012, the county contracted CMar Consulting to facilitate the program. Figure 3.1 shows an overview of components of the current GIS program.

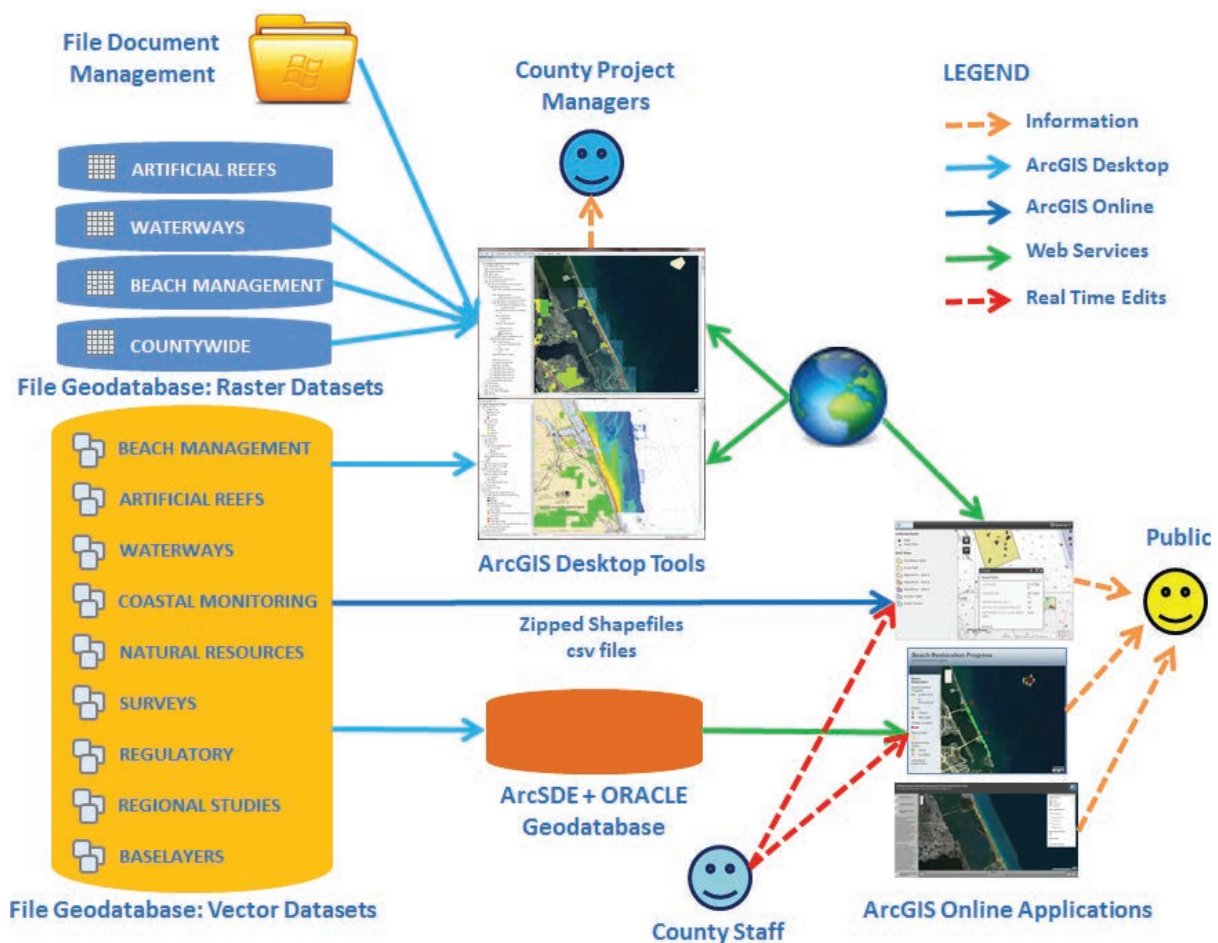


Figure 3.1. Overview diagram of the Martin County Coastal GIS program. Lidar data collected by Brian K. Walker, Nova Southeastern University for the Florida Fish and Wildlife Conservation Commission Fish and Wildlife Research Institute.

At the beginning of 2013, the county had over 20 years' worth of historical and current project information consolidated into file geodatabases (vector and raster). This first program milestone marked the transition and expansion of the program focus from data organization in GIS (file

geodatabases) to tool development providing non-GIS-trained managers and planners easy access to their coastal data.

In less than a year, county project managers had several customized ArcGIS for Desktop maps available to access historical and current program data and help them plan and manage different projects within each program. Access to the data through the desktop map tools allowed the Coastal Engineering Division (CED) staff to start using GIS to manage their own projects. Currently, the ArcGIS for Desktop maps function as planning and management tools and data access tools, which provide easy access to information stored in the geodatabases and the county's file document management system.

In March 2013, the county published its first public ArcGIS Online app to communicate to the public on the daily status and progress of one of its coastal initiatives: the 2013 Hutchinson Island Shore Protection Project. The app went live at the end of March just before the project started. ArcGIS Online tools provide an information pathway to accomplish the county's program goal of providing the public with project information. A second ArcGIS Online app, launched in September 2014 and discussed in detail later in this chapter, provides the public with information about the county's artificial reef program. As this component of the program matures, the county hopes to illustrate the connection between the engineering aspects of a project (e.g., nourishing a beach) and the project's effect on natural resources (e.g., increasing turtle nesting habitat). An example of this connection is the Story Map app featured later in this chapter, which shows sea turtles returning to nest on a nourished beach. The county believes these apps help engage local communities and stakeholder groups.

Currently, updates to the Coastal GIS program and desktop mapping tools from ongoing projects occur two to three times a year as new datasets become available. Efforts during 2014 focused on data consolidation and development; optimization of data access tools for project planning and management; addition of hyperlinks to connect the external file document management system for permits, grants, and other documentation; and the addition of the artificial reef program biological community datasets. Similar efforts are ongoing.

ArcGIS Software Products

The program team looked at ArcGIS Online service to determine the adequacy of that platform to accommodate the county's data access, visualization, management, and analysis needs. Some of the analysis tools that the county uses are part of the ArcGIS 3D Analyst extension. Therefore, in 2013 the project team decided to use ArcGIS for Desktop software to develop the planning, management, and analysis tools and ArcGIS Online to share data with the public. ArcGIS Pro brings a new option to the table, but at this time there are no plans to move away from ArcGIS for Desktop. The county's Information Technology Services (ITS) Division uses ArcSDE software with Oracle to manage other county GIS data. The Coastal GIS program stores data in file geodatabases (see figure 3.1). Datasets that support the Coastal GIS program's ArcGIS Online apps (e.g., Hutchinson Island sea turtle nesting, beach restoration progress, roads) are stored in ArcSDE and published to the web via ArcGIS for Server service.

The following sections of this chapter discuss the strategies and challenges faced by the Coastal GIS program team, including data consolidation and organization, data access, and the development of planning and management tools. The chapter ends with examples of two county programs to illustrate all the components of the Coastal GIS program discussed in this chapter.

Coastal Data Consolidation Strategies

Martin County's diverse habitats, large variety of projects, and, most important, limited funding availability prompted county program managers to identify data consolidation priorities. They had to think strategically to properly rank programs, projects, and datasets within each program to determine which ones should receive funding. Coastal managers require quick access to specific information (e.g., location of the edge of hard bottom over the years or a measure of impacts from beach nourishment) with sufficient detail to enable informed decision-making. Less often, they need access to detailed information (e.g., biological information collected in 40-plus quadrat sampling stations) to complete the decision-making process. All gathered information becomes the basis for prioritization of funding.

Prioritizing Data Consolidation

GIS data consolidation efforts favored engineering and selected natural resource datasets. Priorities included identifying boundaries and limits of topographic and bathymetric surveys, natural resource surveys, and regulatory and engineering design (e.g., dredge and fill footprints, equipment location areas); monitoring locations of environmental and physical survey components (e.g., transects, video survey areas, quadrat locations); and establishing water and sediment sampling locations.

Before 2014, sea turtle, shorebird, and seagrass surveys were the only natural resource surveys with community species data to be included in the Coastal GIS database. Their inclusion was because of the very low number of species identified (fewer than 10) in these surveys when compared with the large number of benthic and fish species surveyed in the natural hard bottom, the natural reefs nearshore (beach restoration projects), and the artificial reefs offshore.

During 2014, the Coastal GIS team started consolidating the biological data. The first priority was to incorporate 14 years' worth of biological community monitoring data (surveyed benthic and fish species) from the county's natural reefs (coral and hardbottom) into the Coastal GIS. The artificial reef data took priority over the beach restoration because the CED wanted to review the biological monitoring protocols for its artificial reefs. The yearlong consolidation and integration of beach restoration projects' biological community monitoring data into the Coastal GIS database started in 2015.

Data Consolidation Challenges

The county receives coastal datasets in many different formats. The same monitoring requirement (e.g., a seagrass survey) in different projects may produce a boundary, a limit or delineation, transects, or detailed biological data quantified through quadrat sampling. In some instances, a single project generates data in all these formats.

Consolidating data for a specific project requires engagement—not only of the county project managers but also of the contractors (and their subcontractors) who produce the data and the permitting agencies that review it. Implementing data submission standards and document-tracking protocols up front to allow seamless data transfer will reduce the extensive time currently required for these “after-the-fact” efforts. As documented later in this chapter, Martin County has already put some standards and protocols in place.

Topographic and hydrographic surveys are the most common datasets produced by coastal projects. The geodatabase currently stores more than 185 surveys, a number that grows every year.

As the number of points associated with these surveys grew, it became unfeasible to store all the points in the system. After looking at several alternative tools (triangulated irregular networks [TINs], mosaics, and light detection and ranging [lidar]), the project team decided to convert all x,y,z survey text and lidar point data to a TIN, and then rasterize the TIN into 5 × 5 ft cells. This raster resolution, much higher than the resolution of most surveys, allows better comparison with higher-resolution lidar surveys (also converted to 5 × 5 ft rasters) conducted in the area.

This survey data format example illustrates the importance of carefully choosing the best option to store a dataset. For coastal planning and management purposes, more important than visualizing all the survey points is the capability to allow users to

- visualize the elevation or depth pattern revealed by a survey (e.g., dune, deeper water);
- delineate an area and quantify area or volume changes relative to an older survey or a reference plan (e.g., authorized channel depth); and
- evaluate erosion and accretion trends in the study area.

With survey data in raster format, users can quickly create contours, extract cross sections, compare surveys, and quantify volume changes, using the commercial off-the-shelf (COTS) tools provided (i.e., 3D Analyst). The x,y,z points for all surveys remain stored outside the geodatabase. Users who want to look at the underlying dataset can follow the hyperlink provided in the survey boundary attribute table to the x,y,z file location. It is a simple step to add that data to the map if desired. Lidar surveys are stored in the original LAS format (also known as LASer, as specified by the American Society for Photogrammetry and Remote Sensing) and accessed through data import/export tools available through ArcGIS software.

Natural resource survey data, the second-most common type of dataset, is the most challenging to store because of the large number of videos and photos recorded in each survey. Permitting rules require the county to collect natural resource data annually for a minimum of two years for artificial reefs and three years for beach restoration projects. Datasets, important in the permitting process, include sea turtle nesting activity, shorebird activity, sea grasses, hardbottom edges, as well as hardbottom extent, location, and communities encountered along monitoring transects and within quadrats. Typically, scientists analyze the biological community data collected during these surveys (i.e., quadrat sampling results), summarize the analytic results in technical reports, and submit the reports to the county and permitting agencies.

Coastal Data Organization Strategies

The data mining and organization required to move the CED to a comprehensive geodatabase has required a substantial commitment of time and money. The expected long-term benefits that justify this investment include improved project planning and management and a reduction in staff time spent gathering information for public records requests and RFIs. Public record requests typically are very detailed and may include “all available data” for a project. Storing project data in the Coastal GIS has greatly improved the county capacity to respond to these requests.

Examples of frequent internal and public RFIs that require quick and easy access include

- surveyor names, costs, and dates in the project areas;
- natural resources in a project area;
- permit or grant monitoring requirements and timelines;
- names of infrastructure owners or maintenance responsibilities;
- quick methods to find and extract data; and
- best ways to display and organize data in desktop maps (e.g., by permit, date, or project).

Data organization in the Martin County Coastal GIS program consists of three components: (1) location of all project-related files in the file document management system; (2) organization of spatial data in easily recognizable feature datasets (i.e., HI_Dredge_Template), feature classes (i.e., HI_Substrate_Quadrats), and tables (i.e., Benthic_Species) in the geodatabase; and (3) groupings of project data and base layers in data access tools. The next sections of this chapter discuss the latter two components in detail.

The county has had an established file document management organization strategy for permit and grant project documentation for several years. Efforts are under way to organize other data eligible for GIS and other ancillary documentation, such as surveys, reports, photos, and videos.

Coastal GIS Data Model and Schemas

Originally based on the Arc Marine data model (Wright et al. 2007), the county coastal data model has evolved to address the needs of the county's coastal programs. The current data model and geodatabase schemas focus on portability and easy access to project information by users untrained in GIS. Because of its role as a public agency, the county required the geodatabase organizers to build in sufficient transparency to simplify responses to public RFIs (e.g., all data related to the Hutchinson Island Shore Protection Project).

To accommodate the “all data related to” types of requests, the project team organized specific feature datasets (vector data only) within the main geodatabase for the beach and waterways programs into project-specific feature datasets with identical schemas (see figure 3.1). Four core feature datasets—survey boundaries and locations, regulatory datasets, base layers, and regional studies—remain in the same dataset because they serve multiple projects.

The chosen data model separates rasters for beach, inlet, and waterway projects into project-specific geodatabases. Isolating the rasters is necessary because of the large volume of topographic and hydrographic survey data produced by the beach management and Saint Lucie Inlet maintenance programs. Furthermore, county ITS division policy requires storage of rasters in file geodatabases. Raster mosaics display faster, are portable, and do not require the overhead of an enterprise database management system (DBMS) such as Oracle.

Project Planning and Management Tools

The project planning and management tool or “desktop map template” solution in ArcGIS for Desktop provides managers with quick and organized access to project data in a GIS. From within a map template, which includes all the data collected for a particular project, managers can copy or remove layers as needed to create individualized desktop maps to address a particular issue.

ArcGIS for Desktop Map Solution

The desktop mapping approach helps ease the pressure on one of the most valuable county ITS resources: storage space. To date, the entire set of Coastal GIS program files occupy 7 GB of disk space, and the size of the majority of the map files (MXDs) created using a template are very small.

Generally, project data in the desktop map tools is organized by program (e.g., one map for artificial reefs, one map for waterway management) or, in some cases, by geographic area. The latter is true for programs with recurrent projects within a specific geographic area (e.g., one map for all the

Hutchinson Island Shore Protection Projects). In areas in which the same program has more than one recurrent adjacent project, one ArcGIS for Desktop map provides access to both projects. This organization enables easy comparison and analysis between past and current projects; in addition, it provides access to all the available data for the project area.

ArcGIS for Desktop Map Organization

All desktop maps include as base layers regulatory and jurisdictional limits, water access, countywide natural resources, transportation, and countywide parcel data (county ITS web service) base layers. Each map also includes aerial photography web services (i.e., countywide or the rectified coastal aerial photography) provided by county ITS and Esri Ocean and World Imagery basemaps. Some programs have unique base layers (e.g., sand sources for beach nourishment) or basemaps such as using a National Oceanic and Atmospheric Administration (NOAA) raster navigational chart (RNC) map service for the artificial reefs, oyster restoration, and waterway maintenance programs.

All desktop maps also include project-specific engineering drawings and hydrographic surveys organized according to project year, project phase, and date. The maps also include natural resource—monitoring surveys organized according to type and date. Organizing the natural resource surveys enhances the temporal interpretation of the data.

Including all these datasets and base layers in the maps rather than adding layers on an as-needed basis allows non-GIS-trained users to find project data quickly without having to sieve through several group layers and folders of project data.

ArcGIS for Desktop Map Optimization

Some recurrent projects have over 20 years' worth of data. Adding all this data to the same desktop map, although advantageous for planning and management purposes, may significantly slow the map's performance.

Establishing visibility ranges for layers or representing data using less complex dataset types (polygon versus raster) when zoomed out has improved the performance of desktop maps. The vast majority of the more detailed datasets become visible only when the user zooms in beyond 1:12,000. Topographic and bathymetric surveys, one of the most common datasets, display the survey boundary when zoomed out beyond 1:24,000 and the survey raster when zoomed in beyond that value.

One raster display property setting, Show Map Tips, provides one of the most useful data display features for desktop maps. Users can view the raster attribute (e.g., depth, relief) by dragging the mouse over the raster cell. The alternative to rasters, contours with labels, requires more resources and provides less accurate data.

Analysis Tools

To facilitate access to the most commonly used analysis and data management tools, the Coastal GIS team created a Martin County Toolset toolbar. The toolset provides access to tools available in toolbars from extensions such as 3D Analyst, which non-GIS-trained staff may find difficult to locate.

The toolbar includes analysis tools such as cross-section extraction, volume calculation, and contour extraction tools that help users accomplish some of the topographic and bathymetric

data analyses described earlier. Other tools often used include Add X,Y,Z Data, Import, Measurement, Buffer, Graphs, Statistics, Hyperlink, and Hypertext Markup Language (HTML) pop-up windows. Funding will determine the schedule for adding planning and analysis tools for each program.

Metadata and Data Submission Standards

Metadata records, one of the most important components of the program, are the most challenging to collect. Presently, the majority of the data consolidated into the Coastal GIS arrives at the county in AutoCAD, shapefiles, spreadsheets, text format, or PDFs, often without metadata. Over the years, the county has attempted to implement data submission standards that include metadata. Such standards are difficult to enforce when dealing with contractors unfamiliar with GIS. In 2014, the county reviewed and simplified its Coastal Data Submission Standards and has implemented them for all contract renewals.

The GIS team continues to build on relationships formed with other contractors during the data-mining process to encourage increased GIS integration into work products. Ultimately, the county intends to require GIS-formatted submittals and thus encourage a more efficient integration of data and metadata into the Coastal GIS. During this transition, open discussion with contractors will help identify compromise solutions to facilitate data delivery and integration into the Coastal GIS that should limit cost increases. The standards provided to contractors include guidelines and examples to encourage better data and metadata record submission. The county currently assumes the increased cost for submitting data in the preferred format.

Case Study Examples

The remainder of this chapter presents two case studies that illustrate the application of all the concepts discussed to this point. The first case study focuses on the artificial reef program and the second on the beach management program, which draws on lessons learned from the Hutchinson Island Shore Protection Project, one of the largest beach restoration projects in Martin County.

The description of each case study focuses on the project's importance to coastal communities, followed by an overview of the types of spatial data produced and dataset organization and description of the planning, management, and public access tools developed to date. The section concludes with a Story Map app, developed to assist the county in public outreach efforts.

Case Study 1: The Martin County Artificial Reef Program

The Martin County Artificial Reef Program (MCARP) started in the 1970s when a group of retirees and sport fishing enthusiasts, led by Bill Donaldson, began a movement to create self-sustaining marine habitats (Martin County Coastal Engineering Division 2006). Presently, the program includes four permitted and active construction sites with a combined total area of 9,700 acres (over 15 sq mi). Permitted active sites include the Donaldson, Ernst, and Sirotkin reef sites (permitted in 1987) and the South County Reef site (permitted in 2007). The latter site lies adjacent to Saint Lucie Hump, a federal marine protected area (MPA) created in 2009. Approximately one-third of the Donaldson Reef site is in state waters (within three miles of shore), and two-thirds lies in federal

waters. All other offshore reef sites are located in federal waters. Because of the costs of obtaining and maintaining state artificial reef permits, the county constructs new reefs exclusively in federal waters.

Depths at the reef sites vary between 50 and 60 ft (15–18 m) in the Donaldson Reef site, between 60 and 70 ft (18–21 m) in the Ernst Reef site, between 70 and 200 ft (21–61 m) in the Sirotkin Reef site, and between 55 and 120 ft (16–36 m) in the South County Reef site. To date, over 100 artificial reef deployments—each constructed at different depths—provide popular fishing and diving spots to locals and tourists (figure 3.2).

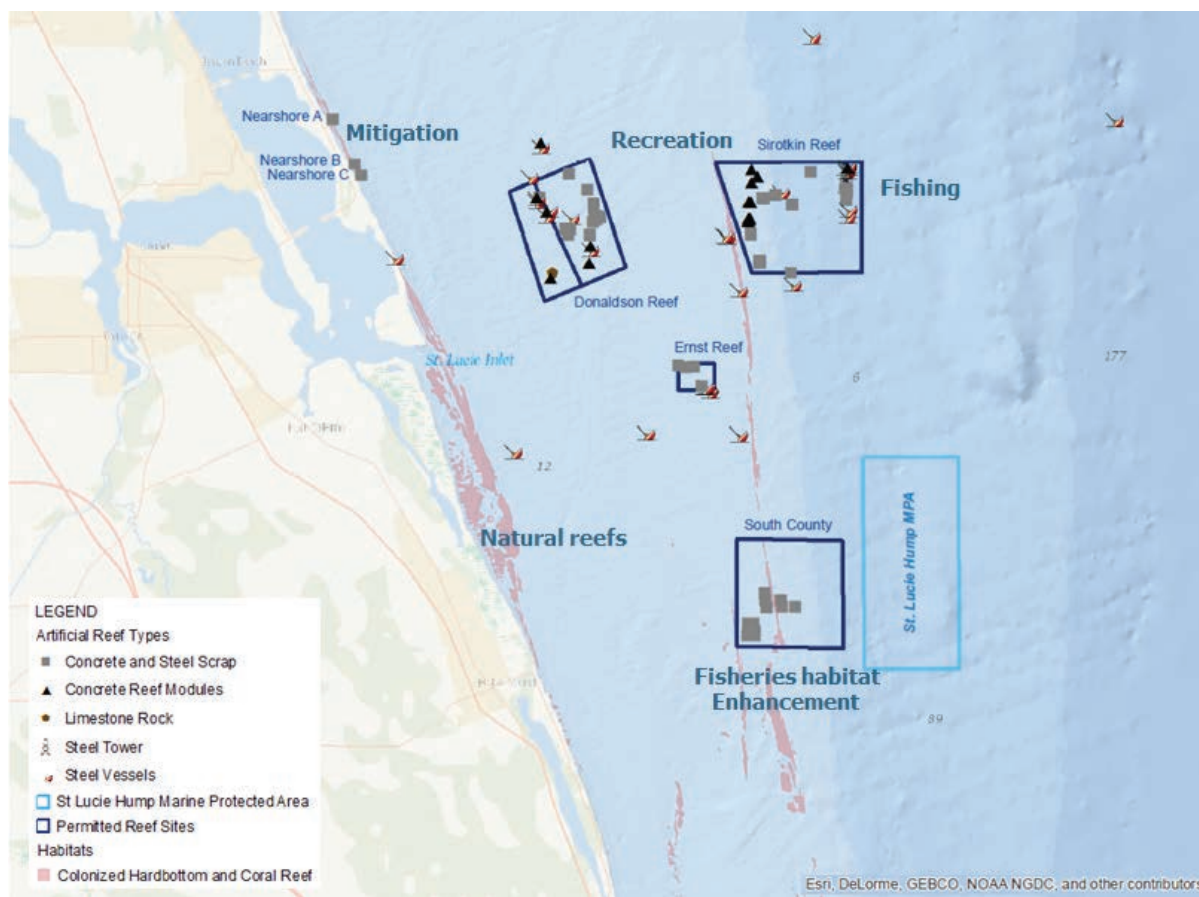


Figure 3.2. Screen capture of the artificial reef site’s permitted site boundaries, primary reef objective, and reef materials. Artificial reef data courtesy of Martin County and CMar Consulting LLC; natural reef data collected by Brian K. Walker, Nova Southeastern University, for the Florida Fish and Wildlife Conservation Commission Fish and Wildlife Research Institute; Ocean Basemap web service courtesy of Esri.

The county also constructs artificial reefs to benefit fisheries by siting a percentage of the reefs in remote locations to minimize their attractiveness for human recreation. This selective placement creates habitat without increasing vulnerability to the nearby natural reefs. In addition to their habitat creation and recreational value, reefs add socioeconomic value to business communities nearby (Johns et al. 2004).

Artificial Reef Program Data

Spatial datasets produced by the artificial reef program include permitted artificial reef site boundaries, deployment boundaries, coordinates of all artificial reefs constructed within each site since the 1970s, and, since 2012, multibeam surveys of the reef area. For each reef deployed, the

county collects water depth; reef relief; qualitative biological data (benthic surveys and fish census) and digital photographs; and video before (discontinued), during, and after construction. Related information for each reef deployment also includes regulatory documents (permits, grants, and reports), cost information, and construction materials and characteristics.

To assure that the reefs meet MCARP objectives and permitting requirements, after construction the county CED monitors each artificial reef deployment once a year for two years, and then adds the reef to an ongoing three- to four-year rotation. Specifically, the CED monitors structural integrity; settling and scouring; and benthic and fish community composition, richness, age, and abundance. These monitoring efforts produce significant spatial and nonspatial data (bathymetric surveys, biological and engineering monitoring reports), photographs, and videos.

In 2012, the county started collecting multibeam bathymetry of the deployed artificial reefs. This type of survey, which provides more accurate and detailed three-dimensional data, facilitates monitoring the life of the reefs as the structures break apart, sink, or disintegrate. Figure 3.3 shows an ArcScene screen capture of two sunken steel ships at the northeast corner of the Sirotkin reef site surveyed in June 2015 (see figure 3.2). Ships surveyed include the steel vessel *Lady Lora* (2003), known as the “Wickstrom wreck,” and a steel barge known as the “tree barge” (2002), located approximately 500 ft to the south. Also visible are the concrete tripod-shape reef modules deployed in 2005 west of the tree barge.

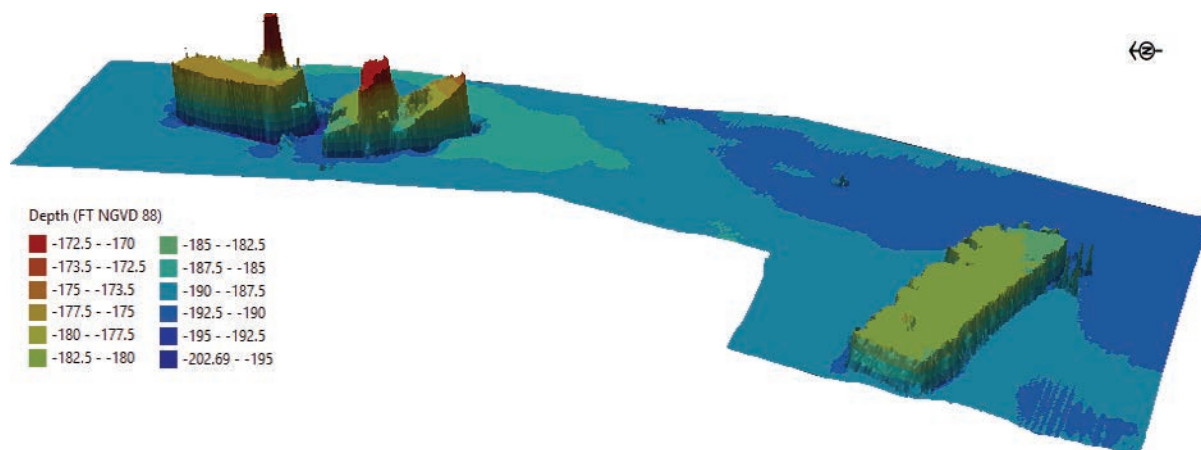


Figure 3.3. Screen capture of the June 2015 multibeam survey of the Wickstrom wreck (left), tree barge (right), and tripod concrete reef modules near the south side of the barge. Data courtesy of Martin County; Maxwell Marine Consulting Engineers Inc.; CMar Consulting LLC.

As mentioned, the county wanted to evaluate whether the current monitoring program provides data that is suitable to assess the performance of the reefs. Specifically, the CED wanted to assure that the data collected to date provides enough information to determine the health and maturity of the artificial reefs’ biological communities. With the reef community data in the Coastal GIS database, project managers and biologists could

- visualize the spatial distribution of individual species on the reef sites (larger scale);
- create a timeline of fish and benthic assemblage changes over time;
- conduct a time-series analysis of the long-term changes of the reef deployments’ species composition, abundance, and age (finer scale);
- fine-tune the 2016 reef-monitoring plan to focus on improving the collection of more quantitative data; and
- relate the observed changes with the natural characteristics of the reef sites, types of materials, and reef design.

Figure 3.4 shows an example of the spatial distribution of protected coral species and of federally managed fisheries species on all reef sites. This distribution is an indication that the MCARP accomplished two of its objectives: creating habitat for protected species and enhancing the fisheries habitats in the region.

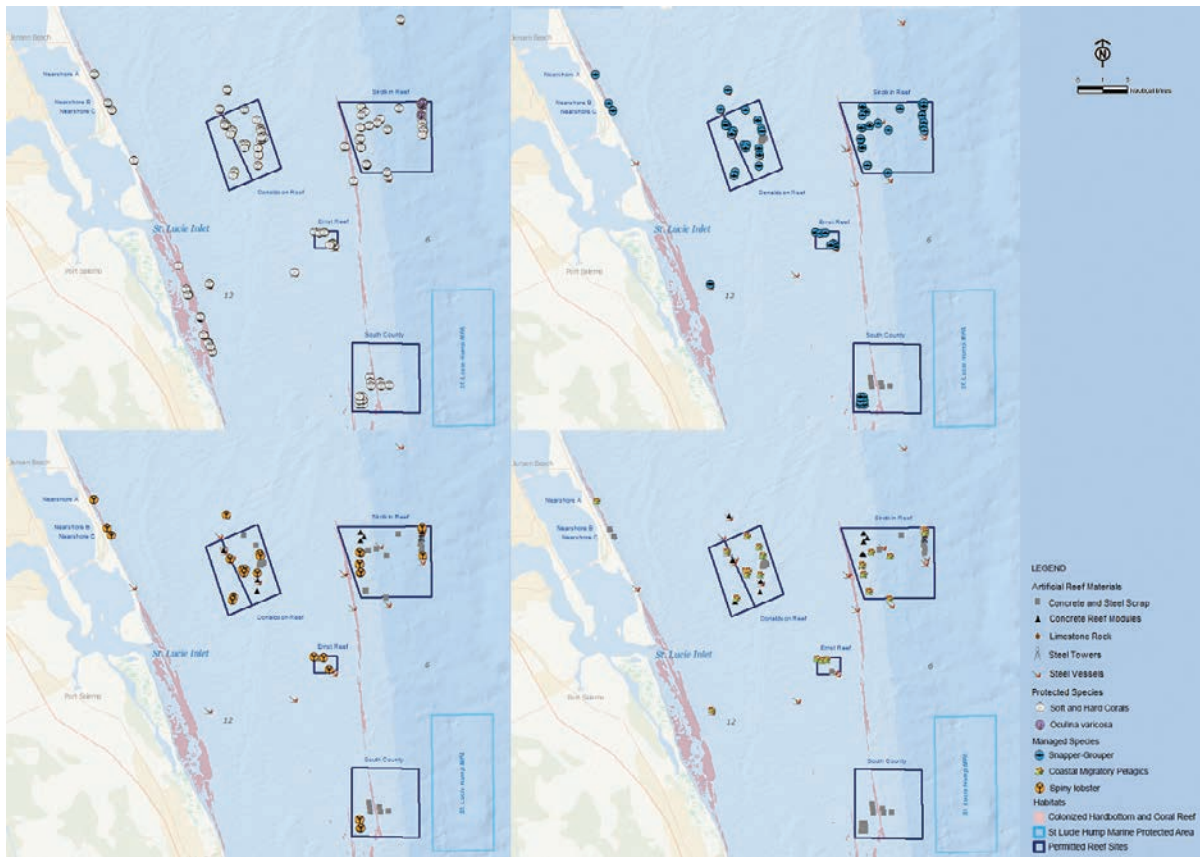


Figure 3.4. Screen captures show the presence of hard and soft coral and protected coral species on the natural and artificial reefs (*upper left*), and managed fisheries in the Martin County offshore reefs (*others*). Artificial reef data courtesy of Martin County and CMar Consulting LLC. Data collected by Lee Harris, Sea Rover Services, and Maxwell Marine Consulting Engineers; Ocean Basemap web service courtesy of Esri.

Like many areas in the southeast Atlantic Ocean, Gulf of Mexico, and Caribbean Sea (US Geological Survey 2009), Martin County's natural and artificial reefs and estuaries are negatively affected (Martin County Coastal Engineering Division 2012) by nonnative, invasive species of lionfish (*Pterois volitans*). Once lionfish sightings (i.e., from fishing tournaments and biological studies) are included in the database, expected in 2016, a close look at the changes in species composition over the past 15 years may provide some insight on the magnitude of the impacts.

In 2016, the county plans to collect quantitative biological data of artificial reef sites (Donaldson and South County reef sites) and adjacent natural reefs to determine whether proximity to natural hardbottom reef (South County reef sites) influences benthic and fish community composition, abundance, and diversity. This data collection effort will add to ongoing community data monitoring (benthic and fish species inventories), conducted every year.

Artificial Reef Program ArcGIS for Desktop Apps

The artificial reef desktop planning tool, one of the first data access apps developed for the county, displays the previously described artificial reef program information in the map tool table of contents. Artificial reef program spatial and tabular data (species lists) is stored in the main geodatabase; survey grids are stored in a raster file geodatabase. The Coastal GIS team plans to finish linking reports, videos, and photos through hyperlinks and customized HTML pop-up windows within the year.

Since 2013, the county uses the desktop map tool to plan the construction of new reef sites and reef diving trails. Because artificial reefs at different depths provide different habitats, county staff uses the map to identify areas with ideal depth, relief, and bottom conditions for the planned reef. Similarly, the tool helps the county determine which reefs are within diving depths and close enough to create a diving trail.

The ArcGIS for Desktop planning tool (figure 3.5) provides easy access to the data stored in the geodatabase and within the county file management system for planning and project management. The map document's table of contents includes the reef site boundaries, all artificial reef projects, reef materials, hydrographic surveys, a grant and permit group hyperlinked to the corresponding documents, links to benthic and fish inventories surveyed between 1992 and 2014, background data to support planning and program management, and basemaps. A scaled-down example of the desktop map app in map document format is included with the digital content provided with this chapter. See "Supplemental Resources" at the end of this chapter for more information.

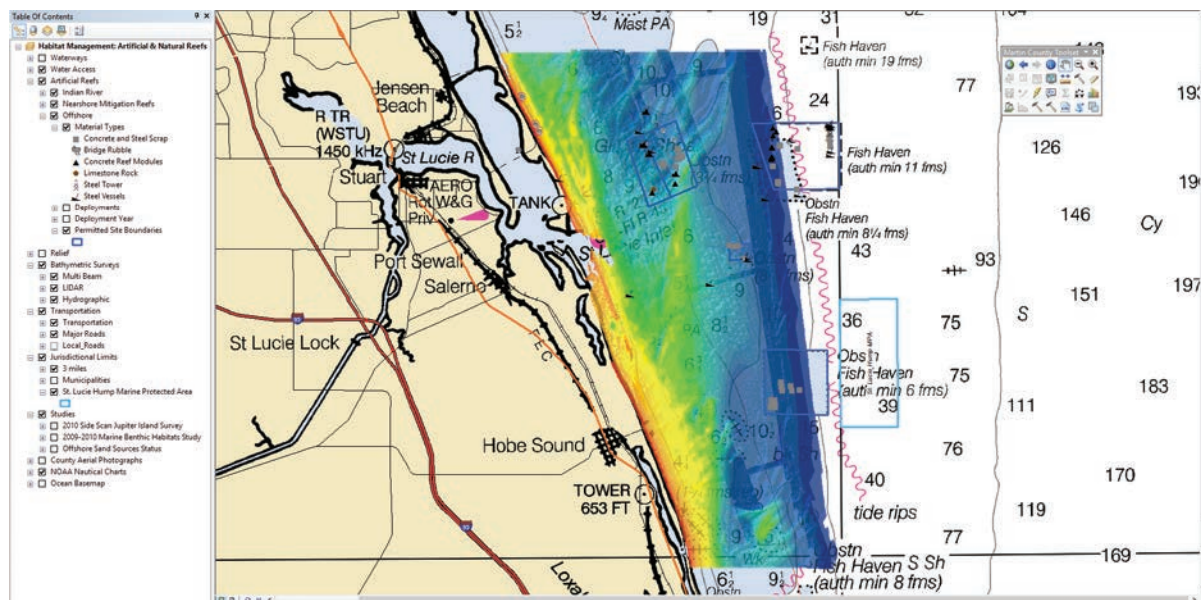


Figure 3.5. Screen capture of the Artificial Reef Program planning tool. Data courtesy of Martin County, CMar Consulting LLC, and the Bureau of Ocean Energy Management Mapping and Boundary Branch; lidar data collected by Brian K. Walker, Nova Southeastern University, for the Florida Fish and Wildlife Conservation Commission Fish and Wildlife Research Institute; web service courtesy of National Oceanic and Atmospheric Administration Department of Commerce National Ocean Service Special Projects and National Marine Fisheries Service.

Background information used for planning and project management includes

- water access locations such as beach parks and boat ramps that provide access to the nearshore and offshore reefs;
- jurisdictional limits (federal and state waters, federal MPA boundaries, cities);
- nearshore and offshore high-resolution bathymetry lidar, relief, and benthic habitat;

- characterization study (Walker 2012) to help guide the placement of new reefs; and
- offshore sand source studies that show boundaries of areas with good-quality sand for beach nourishment. These areas, if not already designated artificial reef sites, are a competing use for future artificial reef site establishment.

The desktop map tool uses the NOAA RNC web service as a basemap. Most artificial reef maps, plots, and images provided to government agencies or the marine industry require nautical charts as background. Alternatively, users can include the Esri Ocean Basemap in the desktop map.

Artificial Reef Program Web GIS Apps

In contrast with the detailed desktop map used for planning and management, the ArcGIS Online web map app (figure 3.6) provides simple and basic location information about the program's artificial reefs to the boating, fishing, and diving communities. Developed in 2014 and embedded on the program website (www.martinreefs.com), it uses the One Pane ArcGIS Online template with the NOAA RNC web service as a basemap.

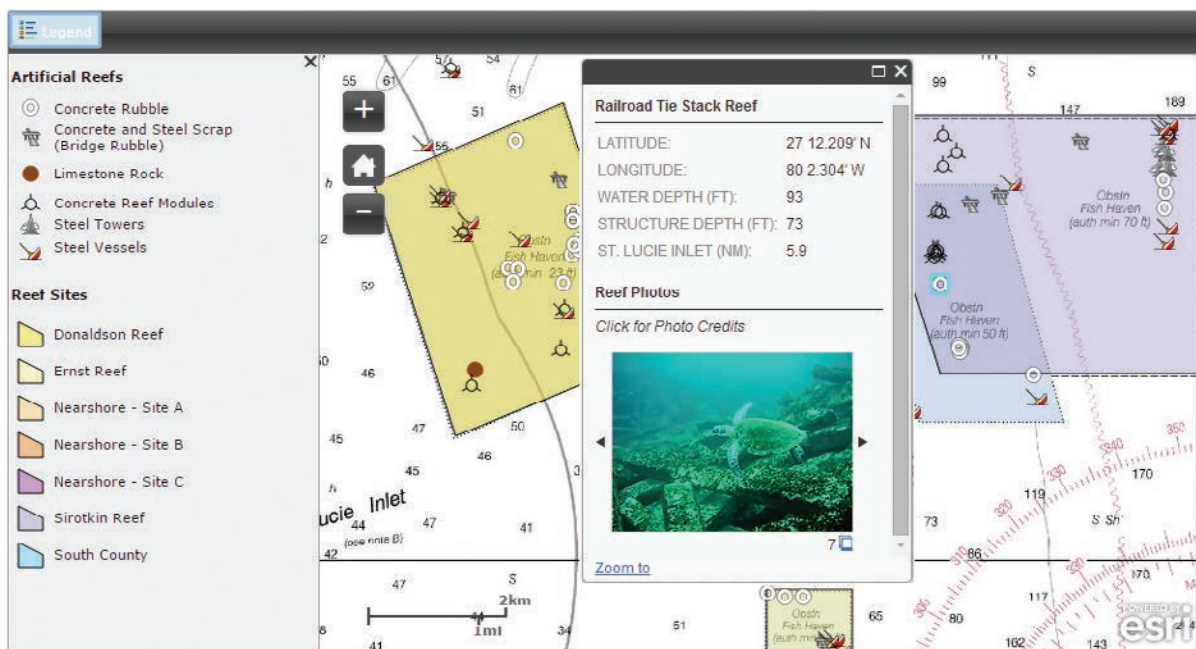


Figure 3.6. Screen capture of the artificial reef locations web map. See also <http://www.martinreefs.com/pages/locations.html>. Data courtesy of Martin County and CMar Consulting LLC; photo courtesy of Martin County; National Oceanic and Atmospheric Administration Department of Commerce National Ocean Service Special Projects.

Information that is available to the public in this app includes reef name and reef materials, geographic coordinates, reef depth, water depth, distance to Saint Lucie Inlet, photos, and a link to the monitoring report if available. Future enhancements will include adding more pictures (see figure 3.6) and developing more complex web apps to promote the sites. Examples include adding a web scene to the map that features all the multibeam surveys of the reefs and apps to engage the fishing community and collect information related to use of the reefs, such as preferred sites and species encountered during the visits. The county will rank these enhancements, match them to various grant opportunities, and implement them as funding allows.

Case Study 2: The Martin County Beach Management Program

Shoreline recession and dune loss along coastal states such as Florida threaten infrastructure and beach habitat, public recreation areas, and the overall economy of coastal communities (Houston 2013). In recent years, severe storms (e.g., Hurricanes Frances and Jeanne in 2004, Wilma in 2005, and Sandy in 2012) altered several sections of the county coast; damaged buildings, roads, and other infrastructure; and displaced thousands of people. Similar to artificial reefs, beach restoration provides a socioeconomic benefit to the county and business communities near and around the beaches. Beaches expand the tax base through enhanced property values, provide revenue from locals and tourist spending at local businesses, and provide employment and income to local residents (Murley et. al 2005).

Storms and wave action that continually erode the Martin County shoreline create increased vulnerability to storm surge and other storm event damage. With a 0.6-mile segment classified as “critically eroded” in 2015, 18.6 of Martin County’s 22 miles of beach fall in this category. The Florida Department of Environmental Protection Bureau of Beaches and Coastal Systems (BBCS 2014) describes critically eroded areas as “areas where erosion and recession of the beach or dune system is such that upland development, recreational interests, wildlife habitat, or important cultural resources are threatened or lost.” Furthermore, the Florida Oceans and Coastal Council (FOCC 2010) projects that “damages will increase as the sea level rises and changing climate produce more powerful storms and higher storm surges.”

Proactive coastal management—maintenance of the dune and beach height, length, and width through restoration projects supported by an intensive physical and natural resource monitoring program—can help minimize, if not avoid, damage from storms.

In a typical beach restoration project, a dredge collects sand from an offshore site and pumps a mixture of sand and water onto the beach. Once the water drains away, bulldozers smooth and adjust the new sand until the beach matches the engineered design profile. An option for smaller areas includes trucking sand from upland sand mines to the beach. Many beach restoration projects include construction and vegetation of shoreline dunes to maintain their ecological value and decrease the risk of erosion and infrastructure damage. The county must carry on the efforts to maintain the coastline (i.e., dredging, transfer, and disposal of sand from inlets and offshore sites into eroded areas) in a manner that improves the shoreline while minimizing impacts to the coastal ecosystem (dunes, intertidal, nearshore, and offshore environments).

Beach Management Program Data

Environmental and physical monitoring efforts required to support beach restoration projects, combined with the engineering and regulatory data associated with each project, make this program one of the most data intensive in the county. Because of environmental permitting requirements, one beach nourishment project may produce over 100 datasets during the project’s life-span (7 to 11 years).

An environmental permit application for a beach nourishment project requires collection of baseline environmental and physical data. Engineers and scientists use this data to prepare construction plans and specifications and establish the physical and environmental resource monitoring protocols. When compared with post-construction data, the baselines provide the means to document project impacts. Similar data requirements apply during the construction phase to ensure that the project meets specifications (e.g., sand size, color, and template). Once a nourishment

project ends, regulatory agencies require three or more years of post-construction monitoring to document the project's performance and unintended impacts to the coastal ecosystem. Because these nourishment projects occur on a 7- to 11-year cycle, this process often starts again soon after the three-year post-project monitoring effort concludes.

Datasets collected before and after construction of a typical beach nourishment project include

- regulatory data (boundaries, leases, limits);
- engineering data (dredge and fill design templates, infrastructure surveys, monitoring stations and locations);
- topographic and bathymetric surveys of both filled and dredged areas;
- natural resource surveys (shorebirds, sea turtles, nearshore and offshore hard bottom, sea grasses, and invertebrates); and
- sediment and water-quality monitoring locations.

Datasets collected during the construction phase of a typical beach nourishment project include

- temporary changes to infrastructure and public facilities to support the project;
- topographic and bathymetric surveys of both filled and dredged areas;
- physical and chemical characteristics of sediment and water; and
- natural resource surveys (shorebirds, sea turtles).

Hutchinson Island Shore Protection Project

The Hutchinson Island Shore Protection Project showcases the Martin County beach management program. Congress authorized the four-mile beach restoration project on August 3, 1995. First construction occurred between December 1995 and April 1996 using sand mined from offshore shoals. Subsequently, the US Army Corps of Engineers (USACE) constructed project segments in 2001 and 2002; and in 2005 and 2013, USACE and the county constructed full projects again in response to the erosion caused by Hurricanes Frances and Jeanne in summer 2004 and Hurricane Sandy in fall 2012. The Hutchinson Island Shore Protection Project, constructed five times, is the county's oldest, largest, and most data-intensive beach nourishment project.

The 2013 Hutchinson Island Shore Protection Project placed approximately 613,000 cu yd of sand on the beach. The hopper dredge mined sand from the Saint Lucie Shoal (a borrow site, approximately 7 mi offshore); navigated to one of two pipelines that extended approximately 1,000 feet offshore; connected to the pipeline; and pumped sand from its hold, through the pipeline, onto the beach. Construction began March 25 and ended on April 22, 2013. While equipment was in the vicinity of the beach and the project was under construction, the county maintained a live web app (described later in this chapter) to inform the public of the project's progress.

Beach Management Program ArcGIS for Desktop Apps

As mentioned earlier, the five projects that comprise the Hutchinson Island Shore Protection Project generated large amounts of data. The sheer volume of information produced by each beach restoration project dictated data organization into individual feature datasets in the main geodatabase and one ArcGIS for Desktop map app for all projects.

After several iterations of data organization, the table of contents for the project area's desktop map now includes four groups: project engineering data, physical monitoring data, natural resources, and base layers and basemaps (figure 3.7). A grant and permit group hyperlinked to the corresponding documents is under development.

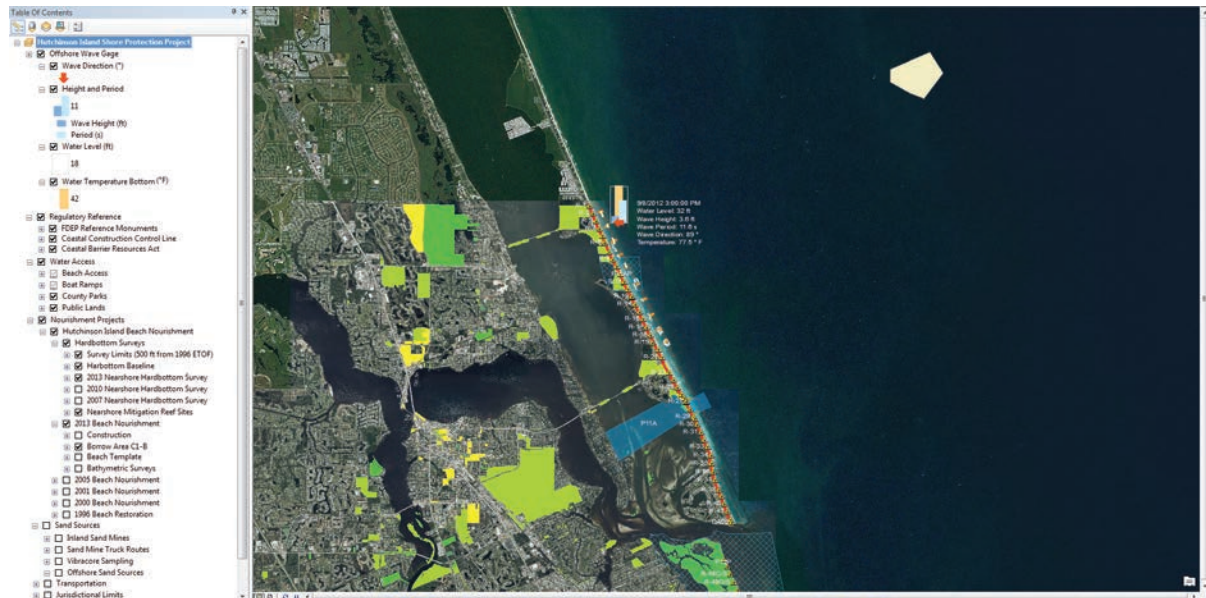


Figure 3.7. Screen capture of the Hutchinson Island Shore Protection Project desktop planning tool. Data courtesy of US Fish and Wildlife Service; Florida Department of Environmental Protection; Martin County; CMar Consulting LLC; Ecological Associates Inc.; Taylor Engineering Inc.; CSA Ocean Sciences Inc.; TNC Oceanographic LLC.

Figure 3.7 shows the Hutchinson Island Shore Protection Project desktop mapping tool. Visible groups include bathymetric and topographic surveys; permitting elements such as borrow areas, beach fill areas, and pipeline corridors; natural resource survey locations; and hardbottom monitoring survey results (e.g., substrate type, edge of hardbottom location).

Natural resource layers are organized in three groups: under Natural Resources, information collected countywide (e.g., sea turtle nesting information); under Hardbottom Surveys, hardbottom monitoring data for the five nourishment projects (1995–2013); and under 2013 Beach Nourishment, information on relocated sea turtle nests during construction and beach scarp formation monitored after project construction but unavailable for past projects.

In addition to project-specific data, a typical beach restoration map includes

- regulatory reference data (e.g., reference monuments, regulatory limits, Coastal Barrier Resources Act units);
- beach access data (e.g., public parks and beach access points);
- shoreline elevation and bathymetric surveys collected annually as part of a countywide coastal monitoring program;
- sand source studies from others;
- land-based sand sources for smaller projects (e.g., sand mine location, truck routes);
- transportation, county parcel information, and aerial photography (the latter updated annually by the county and provided via county ITS as a web service); and
- Esri Ocean and World Imagery basemaps.

A scaled-down example of the desktop map app in map document format is included with the digital content provided with this chapter. See “Supplemental Resources” at the end of this chapter for more information. Base layer data or studies provided to the county by other organizations are not included.

Beach Nourishment Program Web GIS Apps

Before construction of the 2013 project, the project team built one ArcGIS Online app to keep the public informed of the project's progress. Information included the location of equipment offshore, nearshore, and on the beach; aids to navigation characteristics; infrastructure closures (e.g., beach parks often used to store equipment and support the beach projects); and the daily progress of beach sand placement to prevent the public from entering the construction zone.

Because weather and ocean conditions change quickly and affect the timeline for this type of project, the county GIS staff must stay alert to inform the public of schedule changes. The real-time update of the project status through ArcGIS Online feature editing provided another way to introduce GIS into the county's project planning and management workflows and keep the public informed.

The county developed this experimental app to determine the feasibility of using ArcGIS Online for future projects. E-mails demonstrated that the public used the app. A non-GIS-trained staff successfully updated the app daily. The county will likely continue to use this technology for future projects based on the positive reviews from users and other stakeholders.

2013 Hutchinson Island Shore Protection Project Story Map App

To summarize the 2013 project and determine the usefulness and feasibility of these types of apps for future use in the Coastal GIS program, the project team developed a Story Map app. The next sections provide background on the types of information presented in the side panels and web maps and navigation instructions.

The Story Map app uses the Esri Story Map Side Accordion template with a splash screen (figure 3.8) to introduce the project. Data sources include web services for the time-enabled data, a combination of feature layers and data stored in ArcGIS Online, and the Esri World Imagery basemap as background.



Figure 3.8. The 2013 Hutchinson Island Shore Protection Project Story Map app opens with an overview of the project history and 2013 beach nourishment. Photo courtesy of Martin County; splash screen from Story Map app courtesy of CMar Consulting LLC.

The Project Elements web map within the Story Map app (figure 3.9) introduces the project by showing the location of the permitted beach-fill footprint, the permitted Saint Lucie Shoal borrow area (the sand source), and permitted pipeline corridors at both ends of the project.

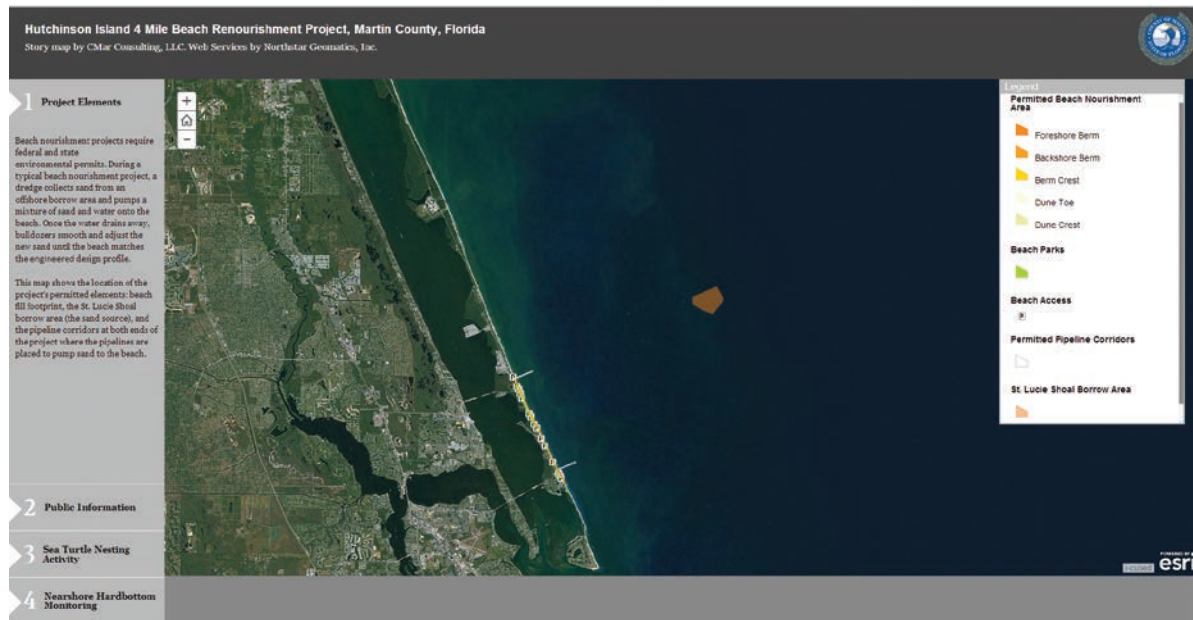


Figure 3.9. Federal and state permitting agencies require project elements to be defined before awarding environmental permits for beach nourishment projects. Story Map app courtesy of CMar Consulting LLC; time-enabled web services by NorthStar Geomatics Inc.; data courtesy of Martin County, Taylor Engineering Inc., and CMar Consulting LLC.

The Public Information web map within the Story Map app (figure 3.10) shows the datasets that are displayed and collected through the ArcGIS Online app developed to inform the public during construction (discussed earlier). Time-enabled layers show the timeline of beach park and beach access closures (red prohibited sign) and sand placement on the beach (yellow line) during beach construction (March 25 through April 22, 2013).

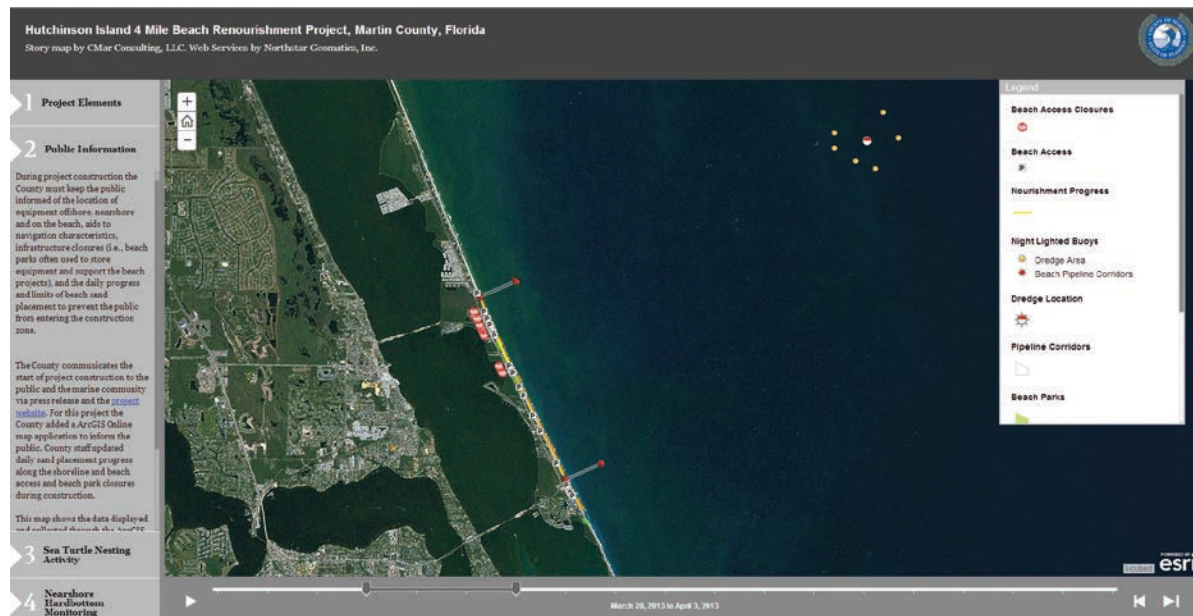


Figure 3.10. Time-enabled map of project's progress and infrastructure closures during beach construction. Story Map app courtesy of CMar Consulting LLC; time-enabled web services by NorthStar Geomatics Inc.; data courtesy of Martin County, Taylor Engineering Inc., and CMar Consulting LLC.

Five species of sea turtles swim in Florida's waters; three of them—the leatherback, loggerhead, and green turtle—nest regularly on Martin County beaches. The Endangered Species Act of 1973 classifies all sea turtles species in Florida as either threatened or endangered. Over 2,000 sea turtles nest each year on Martin County beaches. The Martin County CED and its contractor, Ecological Associates, maintain a comprehensive sea turtle monitoring and conservation program. The program's intent is to ensure that the design and construction of beach nourishment projects maintains the local beaches as vital sea turtle nesting habitat. Monitoring of daily sea turtle nesting activity occurs annually during sea turtle nesting season (May 1 to October 31) to identify any project-induced changes. Turtle-friendly lights are required in sea turtle nesting areas to prevent disorientation of sea turtle hatchlings. Beach lighting surveys twice a year help identify noncompliant lights that are on and near the beach.

The Sea Turtle Nesting Activity web map within the Story Map app (figure 3.11) shows the 2013 nesting season activity before, during, and after the Hutchinson Island Shore Protection Project (March 14 to October 14). The time slider allows the user to visualize nest locations of the first leatherback turtles (in brown); the progress of the beach nourishment project described in the Public Information web map; and the locations of all leatherback, loggerhead (in orange), and green turtle (in green) nests laid on the beach during the 2013 turtle nesting season.

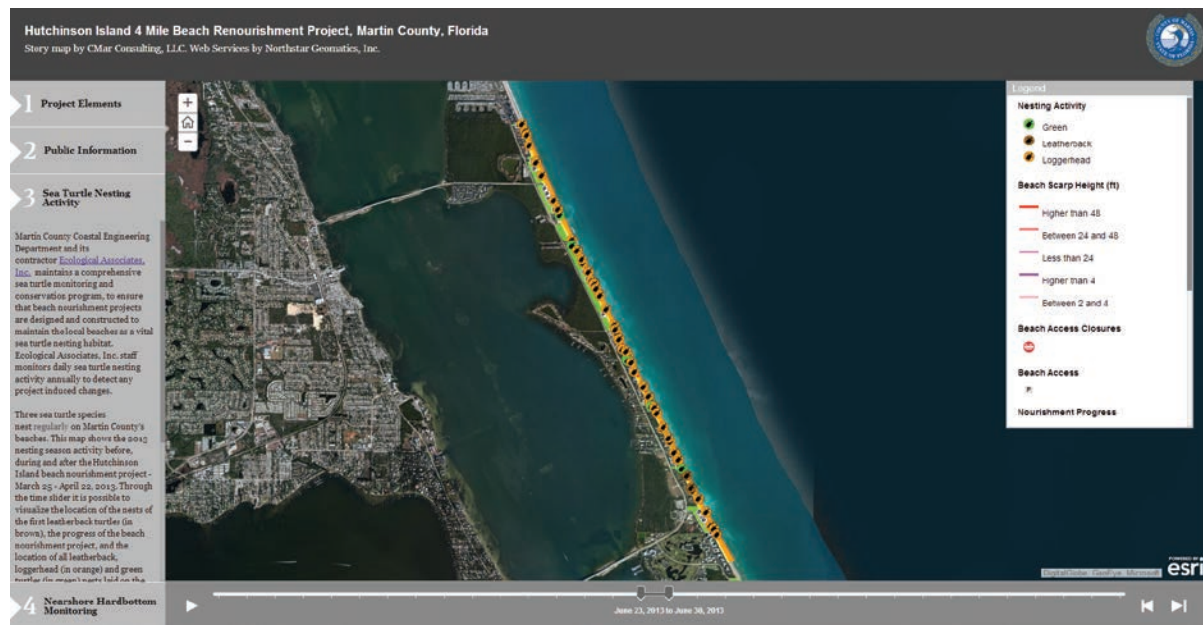


Figure 3.11. Time-enabled map of the 2013 sea turtle nesting along the beach shows the typical seasonal sequence and the peaks of the three species: leatherback, loggerhead, and green sea turtles. Story Map app courtesy of CMar Consulting LLC; time-enabled web services by NorthStar Geomatics Inc.; data courtesy of Martin County, Ecological Associates Inc., Taylor Engineering Inc., and CMar Consulting LLC.

Users can observe beach scarp formation from the end of May through the summer. Steep scarps can prevent sea turtles from crawling up the beach to lay their eggs. Color-coded, shore-parallel lines symbolize beach scarps by height (highest in red, lowest in light pink) in the web map.

The last web map within the Story Map app, Nearshore Hardbottom Monitoring (figure 3.12), shows the eastern hardbottom monitoring limits established during the 1995 permitting of the first project. Figure 3.12 details include the location of the nearshore permanent monitoring transects, video segments, and quadrats established in 2010 to help monitor project-induced beach changes.

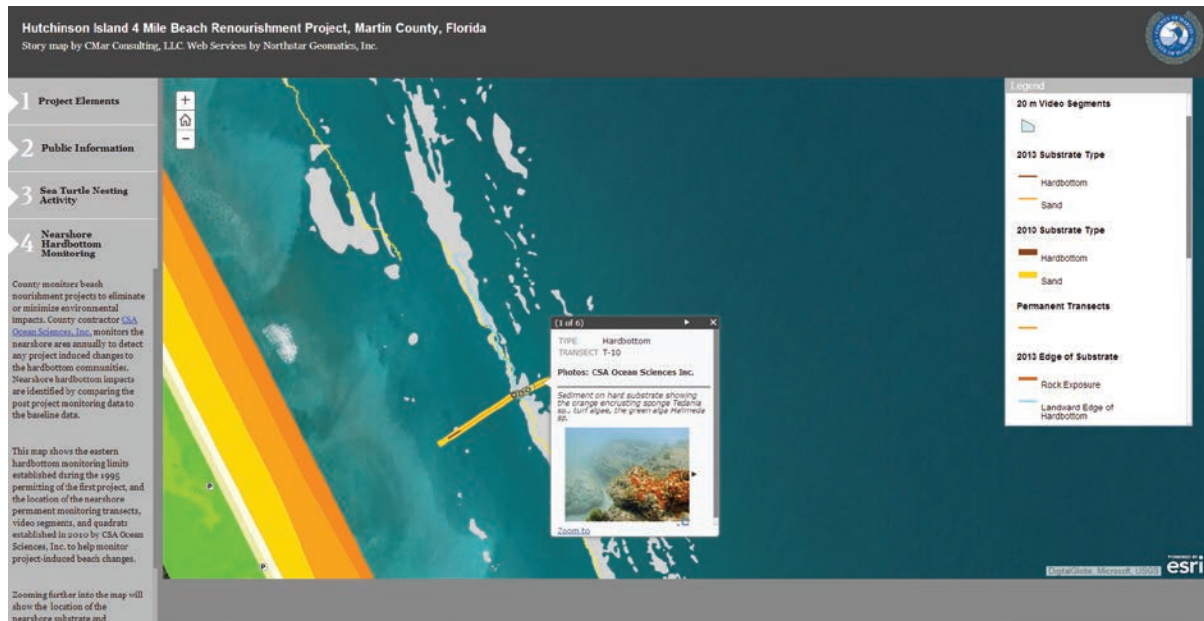


Figure 3.12. Martin County contractors monitor the project area to eliminate or minimize environmental impacts. Comparing the post-project monitoring data to the baseline data identifies nearshore hardbottom impacts. Story Map app courtesy of CMar Consulting LLC; photo courtesy of CSA Ocean Sciences Inc.; data courtesy of Martin County, Taylor Engineering Inc., CSA Ocean Sciences Inc., and CMar Consulting LLC.

In addition to the monitoring locations established in 2010, the fourth web map shows the location of the nearshore substrate and hardbottom edge in 2010 and 2013 and the location of the sand patches along the shore-perpendicular transects in 2010 (thicker, darker lines) and 2013 (thinner, lighter lines). Some transects include underwater photos of the types of species and environments found in an area. Zooming further into the map allows users to view some of these photos.

Final Considerations

The data model, geodatabase schemas, maps, and tools described in this chapter show only a few components of the Martin County Coastal GIS program. The county is close to having a full coastal program data model portable to other coastal counties that have similar projects and programs.

Data Model and Geodatabase Schema

The data model and geodatabase schemas discussed in this chapter reflect the data monitoring requirements in the State of Florida; however, any region with similar projects will benefit from the work completed for Martin County to date.

The data model and geodatabase schemas are easy to adapt to other geographic areas, but the Martin County project team recommends that any applications of the data model and geodatabase schema be preceded by a thorough review of the spatial data available for the new area and an assessment of the GIS skill level of the new users of the data access tools.

GIS specialists on the Martin County project team face ongoing challenges, specifically coordinating the needs of county project managers within the parameters set by county ITS and

finding the most efficient way to organize the data and develop the necessary tools. The data model's current organization, the file versus ArcSDE geodatabase option, and the desktop map solutions discussed earlier provide good examples of strategies devised by the development team to allow the Coastal GIS program to advance.

As the program matures, the goal is to move all vector data to an enterprise spatial database engine (SDE) geodatabase and provide quarterly updates to the public version managed by county ITS. In the interim, county ITS agreed to keep data in file geodatabases until the system is fully developed and tested. ArcSDE and Oracle implementation began in fall 2015.

Desktop Tools

In spite of the large amounts of information that the county accesses, the desktop maps are adequate to provide a good project planning and management tool. Still, the Coastal GIS program team intends to streamline these desktop maps further to improve project management workflow.

The program team has considered separating the largest desktop maps (i.e., from beach or inlet projects) into less data-intensive individual project maps (i.e., by year or permit). Unfortunately, the same data often, as each project rolls into the next, serves as the last monitoring event from one project and the baseline for the next one. In addition, because of the cost of collecting data, it is also common to use the same dataset to address the permit monitoring requirements of multiple projects.

Accessing simple information through ArcGIS Online web maps can help answer some of the most frequent internal or external RFIs (i.e., countywide natural resource and bathymetric survey location), but county staff cannot perform analysis on the data. Furthermore, the more detailed public record requests may include data that should not be readily available to the public. In this case, the organized file system and GIS planning tools are the best solution to gathering data.

As county staff continues to use these desktop maps and makes the transition to a planning and management workflow that relies more on GIS, options to streamline the desktop maps for project management will become clearer for both county managers and GIS specialists as they monitor how the county uses the desktop tools. One strategy to monitor that use includes a short monthly report on how users employ each desktop tool. Collected information will include (1) program and project details, (2) desktop template used, (3) toolbar buttons used, (4) issue addressed, and (5) a brief description of the work done and data used.

The Story Map Approach

The Esri Story Map app appears to offer significant benefits to the county GIS program. In this case, the Hutchinson Island Story Map not only tells the story of the project but also integrates the time variable to show various phases of the project (i.e., beach permitting, construction, and monitoring [turtle nesting, scarps, and hard bottom]). This visualization provides an integrated view of the project and an opportunity to educate stakeholders and the public on the effects of beach nourishment on turtle nesting and hardbottom reefs.

Typically, permitting agencies receive project information in a lengthy report seldom viewed by the public. The county plans to continue developing new web apps (i.e., Story Map apps) to provide project information to the public and other stakeholders. The capability to tell a project's story and integrate the several project elements and visualize them is powerful. The Esri Story Map approach has potential to reach government, stakeholders, and the public in a simple and succinct way.

Acknowledgments

Two of the original project visionaries—Dr. Alexandra Carvalho with CMar Consulting and Kathy Fitzpatrick, Martin County’s coastal engineer—have been responsible for the majority of the work done since the project’s inception, and they remain the primary forces behind the program. With the team since the beginning and representing Martin County’s ITS Division is Frank Veldhuis with NorthStar Geomatics. Veldhuis ensures that the Coastal GIS program complies with the county’s GIS standards and requirements. In his other role as enterprise geodatabase manager, he will eventually assure the system’s implementation on the county ITS enterprise platform. Veldhuis also publishes all web services needed for the web and desktop apps.

Baret Barry, former county environmental manager, has been associated with this effort for several years owing to her involvement with the Martin County Artificial Reef Program. Existing data for the reef program became the prototype for this larger program; thanks to Barry’s data checking, updates, and corrections, the effort progressed from an idea to the current version. The most recent addition to the team, Jessica Garland, associate county project manager, is the most active user of the system. Quickly becoming a GIS power user, she has been an essential member of the team, providing feedback on every product developed.

The Coastal GIS program relies on extensive collaboration with all other Martin County contractors, data providers, county collaborators, partners, grantors, and so forth, that warrant acknowledgment. They include agencies such as the Florida Fish and Wildlife Conservation Commission, Florida Department of Environmental Protection, US Army Corps of Engineers, National Fish and Wildlife Foundation, National Oceanographic and Atmospheric Administration, and county contractors: Ecological Associates, CSA Ocean Sciences, Taylor Engineering, Atkins North America, Morgan & Eklund, Lee Harris, Sea Rover Services, Maxwell Marine Consulting Engineers, and TNC Oceanographic.

The comments and suggestions of two anonymous reviewers greatly improved this chapter.

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Supplemental Resources

Dawn J. Wright, ed.; 2016; *Ocean Solutions, Earth Solutions, second edition*; http://dx.doi.org/10.17128/9781589484603_3d

For the digital content that goes with this chapter, explained below in this section, go to the book's online resources (esri.com/esripress-resources/ocean-solutions-2e). A link and QR code are provided here for the Story Map app.

Martin County, Florida, Artificial Reef Planning Tool Example

This project shows an example of an artificial reef program planning tool that consolidates its data for future reference and planning of new projects. This example can be a starting point for other areas with similar programs. For convenience, an XML schema of the geodatabase as well as ArcGIS Diagrammer tool is included together with the map document and geodatabase that contains the data for the location of all the offshore reefs in Martin County, Florida (courtesy of Martin County Coastal Engineering Division).

2013 Martin County, Florida, Beach Restoration Planning Tool Example

This project shows an example of typical spatial datasets collected for beach restoration projects in Florida and a planning tool that consolidates its data for future reference and planning of new projects. It includes three phases of the project: permitting, construction, and monitoring of natural resources. This example can be a starting point for beach restoration in other areas. For convenience, an XML schema of the geodatabase as well as ArcGIS Diagrammer tool is included together with the map document and geodatabase that contains the data for the 2013 Hutchinson Island Shore Protection Project (courtesy of Martin County Coastal Engineering Division).

Hutchinson Island Story Map

Go to <http://esrimapbook.esri.com/hutchinsonisland>.



CHAPTER 4

Tools for Implementing the Coastal and Marine Ecological Classification Standard

Lori Scott, Kathleen L. Goodin, and Mark K. Finkbeiner

Abstract

NatureServe and the National Oceanic and Atmospheric Administration have led the development of the Coastal and Marine Ecological Classification Standard, which provides a comprehensive national framework for organizing information about coasts and oceans and their living systems. This Federal Geographic Data Committee–approved standard includes the physical, biological, and chemical data used collectively to define coastal and marine ecosystems. Designed for use within all waters ranging from the head of tide to the deep ocean, the Coastal and Marine Ecological Classification Standard offers a common framework and language to unify inventory and mapping approaches for coastal and marine ecosystem data. It is compatible with existing upland and wetland classification standards and can be used with most, if not all, data collection technologies. Because of these characteristics, this standard allows scientists to use and compare data from various sources and time frames. As a standard lexicon, this classification standard makes aggregating the data more efficient and will ultimately support more compatible coastal and marine assessments and resource management efforts in nearshore and offshore environments. Users now need Coastal and Marine Ecological Classification Standard–compliant data collection, data entry, and data management tools to support consistent application of the standard. This chapter describes how the coastal and marine user community can apply the NatureServe observation toolkit and the National Oceanic and Atmospheric Administration’s crosswalking tool for the Coastal and Marine Ecological Classification Standard to support more effective and standardized field data collection, upload, validation, aggregation, integration with existing data, and publication. The online toolkit allows users to enter, manage, and share Coastal and Marine Ecological Classification Standard data efficiently and flexibly, and a suite of data templates specify the fields that are essential for Coastal and Marine Ecological Classification Standard–compliant observations. Users can customize the templates as needed to accommodate additional survey-specific data. The design is compatible with Federal Geographic Data Committee and International Organization for Standardization metadata standards.

Introduction

Observational data of species and ecosystems is fundamental for scientific inventory and monitoring, conservation planning, habitat management, invasive-species assessments, predictive distribution modeling, and more (National Oceanographic Partnership Program 2010; Duffy et al. 2013). The structure of these datasets can vary greatly depending on the source and intended use, making it difficult to gain a comprehensive picture of biodiversity within an area. Integrating disparate biodiversity data to maximize its utility to support decision-making continues to challenge resource managers and conservation practitioners.

The first step in integrating observation data is consistently classifying the units to be aggregated. Until recently, there was no consistent US national classification for observing, mapping, and integrating marine ecosystem observation data. The Coastal and Marine Ecological Classification Standard (CMECS) now provides the classification framework and definitions for consistently identifying and naming ecosystem units (FGDC 2012).

The second step is documenting observations in the field and applying the correct standard name to the observed units. Identification of the “what is it?” for ecosystem observations is not trivial: it is hard work to document the attributes (or *classifiers*) that allow you to assign the right name to a given ecosystem.

The third step in integrating observation data is identifying existing data and data products such as maps that are labeled with nonstandard names. Or you can translate or “crosswalk” (i.e., convert) these data products into the standard so that they can be integrated with other CMECS-compliant observation data.

The fourth step is compiling these datasets into a common database, supplementing them with supporting data as needed, and making the data and data products widely available to support decision-making. NatureServe and the National Oceanic and Atmospheric Administration (NOAA) are partnering to streamline the data integration process by developing the standards, methods, and tools for integrating and sharing coastal and marine ecosystem observation data on national and international scales. In this chapter, we describe the tools of CMECS and how they can be used to collect, validate, aggregate, integrate, share, and publish marine ecosystem observation data.

Background

NatureServe represents an international network of biological inventories, known as natural heritage programs or conservation data centers, operating in all 50 US states, Canada, Latin America, and the Caribbean. As a unit, it not only collects and manages detailed local information on plants, animals, and ecosystems, but also develops information products, data management tools, and conservation services to help meet local, national, and global conservation needs.

NatureServe’s Role as a Standardized Biodiversity Observation Network

To advance its mission of providing the scientific basis for effective conservation action, NatureServe develops standardized methods and associated tools designed to improve the ability of field biologists to record, manage, and share geospatially explicit observation data. Benefits of NatureServe’s observation data toolkit include (1) improving the accuracy, precision, and documentation

of geospatial data for inventories of species and ecological communities and decreasing the time from data capture to data sharing; (2) increasing the efficiency and productivity of field researchers by introducing elements of location-aware computing into the field data collection process; and (3) enhancing information sharing and interoperability among observation data collections, observation-oriented data networks, and communities of practice.

NOAA Office for Coastal Management's Role in CMECS Tool Development

NOAA has broad national responsibilities related to fisheries management, habitat conservation, navigation, geodesy, and meteorology. Many efforts are under way within NOAA in which CMECS is relevant, and NOAA is the steward agency for the standard. Within the NOAA National Ocean Service (NOS), the mission of the Office for Coastal Management is to link science and best practices to coastal management. The center routinely partners with agencies at the federal, state, and local level, as well as academic institutions, nonprofit organizations, and the private sector to help ensure that managers have access to the best tools and data for their work and that researchers have an understanding of how their results can inform management decisions.

Geospatial tools that support data synthesis, analysis, and product development are a key element of the center's mission. The Office for Coastal Management has developed a GIS tool to automate the translation and conversion of existing spatial ecosystem data into CMECS. The center will ensure that this tool can be integrated with other geospatial tools, applied in commonly used software environments, and crafted so that it can be incorporated into existing workflow processes, including the NatureServe observation toolkit.

Overview of CMECS

CMECS provides a comprehensive framework for organizing information about coasts and oceans and their living systems. This information includes the physical, biological, and chemical data collectively used to define coastal and marine ecosystems. The standard was designed to meet the needs of many users, including resource managers and planners, conservation practitioners, engineers, mappers, and researchers from government, industry, and academia that need to describe, map, or assess coastal and marine ecosystems. CMECS is the result of an ongoing collaboration among several organizations, including NatureServe, NOAA, the US Environmental Protection Agency, US Geological Survey (USGS), and University of Rhode Island with input from dozens of professional scientists and marine managers (see appendix J of FGDC [2012] for a complete listing). The Federal Geographic Data Committee (FGDC) has approved CMECS as a US federal standard (2012).

The CMECS framework is organized into two settings, biogeographic and aquatic, and four components: water column, geoform, substrate, and biotic (figure 4.1). Each element describes a separate aspect of the environment and biota. Settings and components can be used in combination or independently to describe or map ecosystem features. The hierarchical arrangement of units within the settings and components allows users to apply CMECS to the scale and specificity that best suits their interests. Modifiers allow users to customize the classification to meet specific needs. Biotopes can be described when there is a need for more detailed information on the biota and their environment. An online catalog of the units with complete definitions is also available from NatureServe (2013).

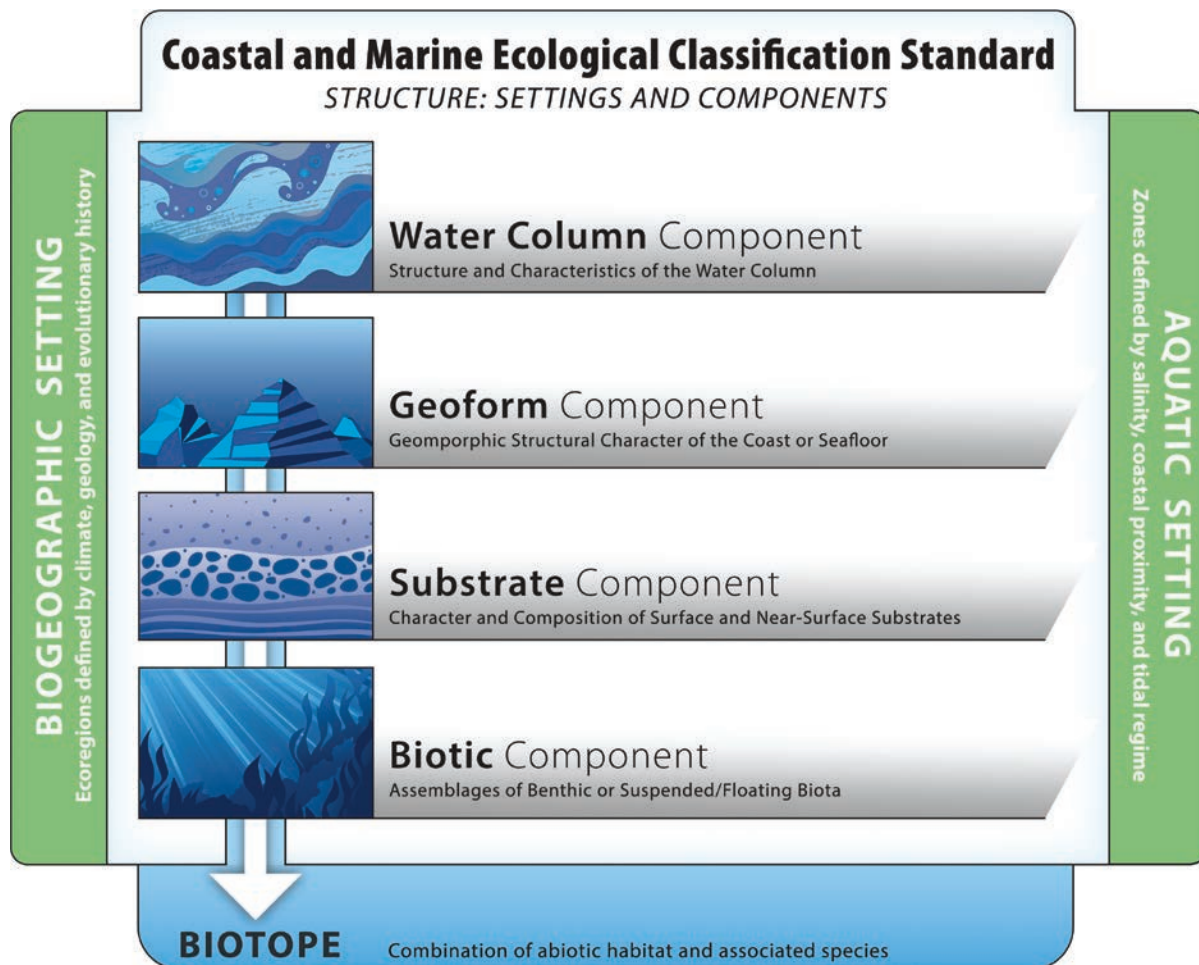


Figure 4.1. The Coastal Marine Ecological Classification Standard organizing framework shows the structure of the settings and components.

Designed for use within all waters ranging from the head of tide (as defined in FGDC [2001]) to the deep ocean, CMECS offers a common framework and language for unifying inventory and mapping approaches for coastal and marine ecosystem data. It is compatible with existing upland and wetland classification standards such as the National Vegetation Classification Standard (FGDC 2008) and Classification of Wetlands and Deepwater Habitats of the United States (FGDC 2013) and can be used with most, if not all, data collection technologies. Because of these characteristics, the standard allows scientists to use and compare data from various sources and time frames.

As a standard lexicon, CMECS makes aggregating the data more efficient and will ultimately support more compatible coastal and marine assessments and resource management efforts in nearshore and offshore environments. Users now need CMECS-compliant data collection, data entry, and data management tools to support consistent application of the standard as well as data sharing.

Modeling Observation Data

Well-established data standards for biological observations and an active biodiversity informatics community contribute to the ongoing development and adoption of these standards. The Biodiversity Information Standards Taxonomic Databases Working Group (TDWG) is one such initiative that promotes standards for the exchange of biodiversity data (TDWG 2014). TDWG recognizes Darwin

Core (TDWG 2009b) and Access to Biological Collections Data (ABCD) (TDWG 2009a) as the two most widely deployed formats for biodiversity occurrence data.

Historically, these standards have been developed and applied retrospectively to existing observation data, usually found in museum specimen collections. Applying these standards has enabled researchers and other users to use well-defined access protocols to query hundreds of millions of occurrence records mapped to the Darwin Core schema and published by institutions worldwide through the Global Biodiversity Information Facility (GBIF) (2014). A limitation of these schemas is their inability to integrate observations that represent different levels of biological diversity, from genes to species to ecosystems. The Darwin Core schema is typically used to describe flat data structures, which works well for an observer who is describing an observation of a species present at a given place and time. However, the specimen-based schemas do not adequately address more complicated biological assemblages (e.g., vegetation, biotic communities, and so forth) and ecosystem observations that require documentation of detailed biotic data (e.g., species composition, structure, individual species traits) as well as detailed abiotic data (e.g., substrate, geologic formations, hydrologic attributes [Wiser et al. 2011]). These types of observations may also entail more complicated sampling methodologies that include multiple nested sampling units (such as points along transects or plots and subplots).

The observation toolkit's underlying schema in turn accommodates a wide diversity of data models, including those for biological assemblages that require hierarchical or nested observation data structures. Figure 4.2 shows how the toolkit accommodates data models ranging from simple species observations to more complex models that incorporate all the CMECS components. The core data model provides a means of recording an observation that, at a minimum, documents (1) what biological entity occurs, (2) at what location, (3) at what time, and (4) as observed by whom. To document the biotic component of CMECS, the model captures supporting data for the information needed to appropriately assign a standard name to the biotic assemblage, and then provides for additional locational, environmental, and taxonomic information that allows further characterization and classification.

The established standards also have a limited ability to integrate data from disparate data sources without losing potentially valuable, unique fields of information that do not fit the standard's core. By definition, data standards involve trade-offs that must balance the value of unique information housed in individual data collections versus the value that comes from being able to combine these pieces of information into a common database with a shared schema. Over time, communities of practice have adopted extensions of the Darwin Core to accommodate these differences (for example, the Marine Biogeography Extension developed by Ocean Biogeographic Information System-USA [OBIS-USA] [USGS 2014]). The observation toolkit offers a unique solution that supports retrospective crosswalking of legacy data to a standard classification system and data model without leaving behind nonstandard but project-relevant information. It also offers tools for communities of practice to create and share standardized templates that help harmonize new data collection efforts.

Another impediment to large-scale synthesis of biodiversity observation data is the inability to retrospectively reconcile the taxonomy for species names documented in biological assemblage observations. Taxonomic standards can vary over time and space, and different individuals can use the same name to represent different taxonomic entities (Wiser et al. 2011). When only names are included in the observation dataset instead of taxonomic concepts (i.e., references for the species circumscription), the meaning of the species listed can be ambiguous. This uncertainty in species taxonomy can impede efforts to integrate data. The observation toolkit uses dynamic web services to relate individual observation records to concept-based taxonomic references, ensuring that information is not lost when taxonomic changes occur.

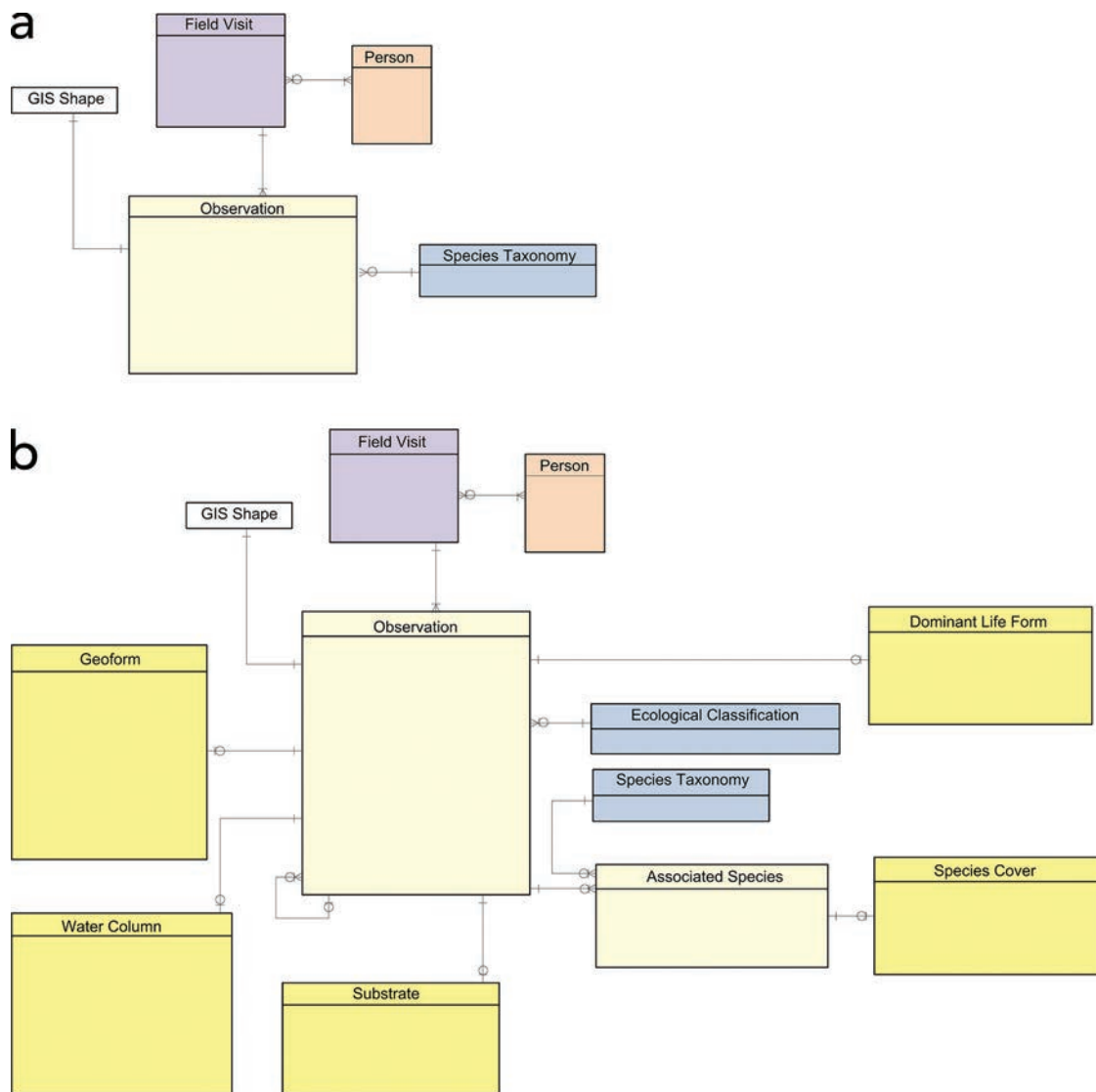


Figure 4.2. The (a) core data model for species observation compared with the (b) enhanced data model for Coastal Marine Ecological Classification Standard component observations.

Observation Toolkit Components

NatureServe's observation toolkit consists of several components that allow integration of data from across levels of biological organization into a single biodiversity observation database (figure 4.3). The components summarized here are described in detail in the following sections.

- **Template Library:** an online collaboration tool for creating and sharing data collection survey forms that meet community standards while supporting project-specific customizations.
- **Kestrel:** an online, spatially enabled observation database that supports import or manual data entry into Template Library–authored survey formats and facilitates data sharing among users.
- **Mobile tools for field data capture:** the toolkit is compatible with Windows Mobile GPS-enabled devices and integrates with ArcPad software for field access to reference maps.
- **ArcGIS for Desktop Editor:** utilities for offline data entry, validating, and exporting results.

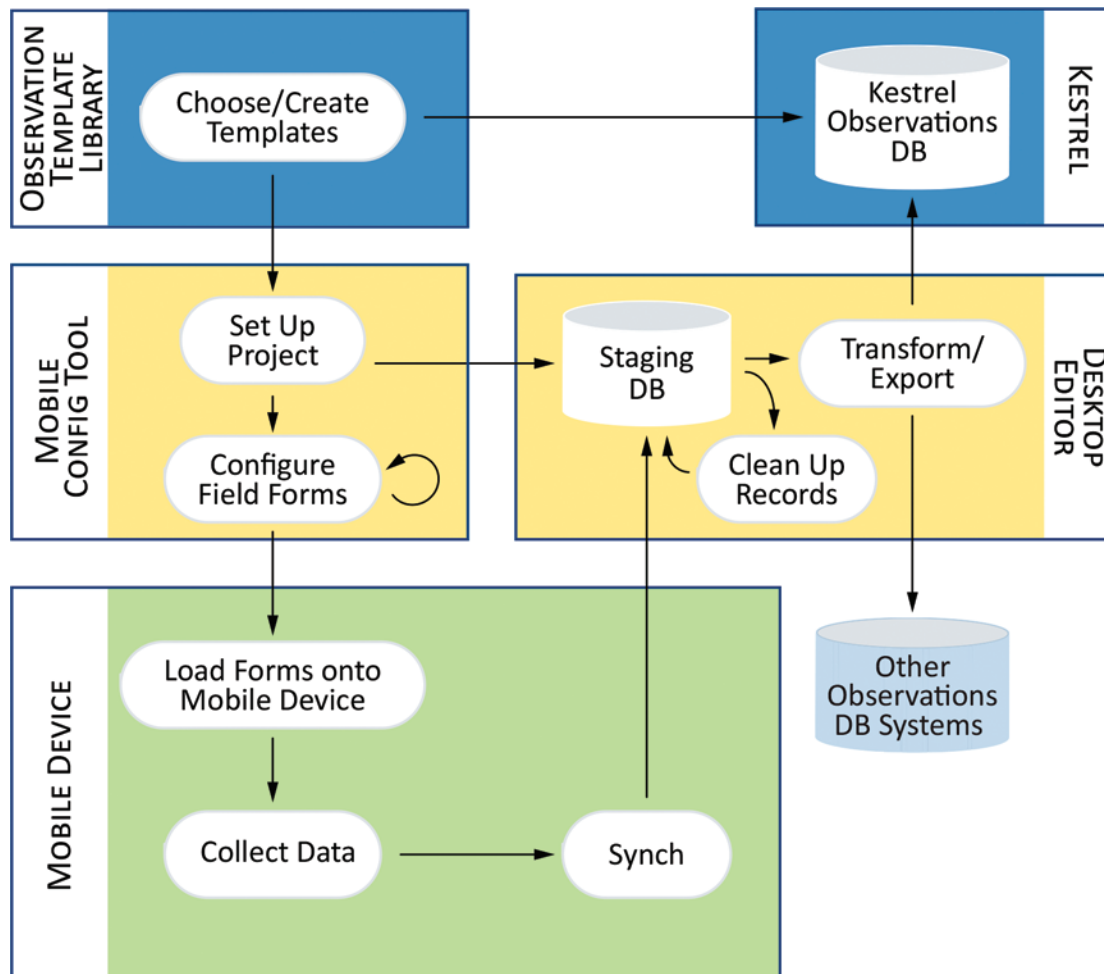


Figure 4.3. The observation toolkit includes technology components that support more efficient field collection, management, and sharing of observation data.

Observation Data Templates: Support Standardized Data Collection and Validation

Observational data formats can vary widely to accommodate unique data collection protocols and study designs. However, a small subset of core attributes minimally defines any observation: what was seen, when, where, and by whom. The observation toolkit embraces diversity among observation data formats while promoting greater consistency and standardization among data collections. It does this by providing tools to allow users to discover, adapt, reuse, and share observation data templates. A template is a collection of individual data fields or attributes and associated validation rules that define the minimal set of information that must be recorded for an observation according to a data collection protocol. For example, a template can define which attributes are optional and which are required, and a given attribute definition can specify its allowable field values or ranges. The template also provides multilingual labels and help text for each attribute. The template structure, attributes, and validation rules are supported by a standardized schema, allowing the template to be expressed, downloaded, and shared in an extensible markup language (XML) package.

New CMECS-compatible templates assist users in entering data that is compliant with CMECS by including field values that are consistent with the standard's unit definitions, cascading drop-down lists that accommodate the standard's hierarchical data fields, and data validation rules that

enforce valid combinations of standard units. Users can develop and share customized templates to accommodate different sampling gear and sampling methods and additional project-specific data.

Templates can be deployed through offline and mobile devices for documentation of field-collected samples in the lab and through online tools, including Kestrel. Templates can be designed to accommodate FGDC and International Organization for Standardization (ISO) metadata standards (ISO 2014) as well as the Darwin Core species observation data standard, among others.

Template Library: Supports Authoring and Sharing Reusable Templates

Templates are created and made available through the Template Library. The Template Library is a companion online resource for toolkit users for authoring, sharing, and reusing customizable survey templates for use with Kestrel and mobile field data collection tools. The Template Library supports a wide variety of observation data structures and data collection protocols, including rare-species sightings; species lists and environmental data collected in quadrats, along transects, or using other sampling schemes; time-series monitoring data; and ecological-integrity assessment data. Users can select and modify an existing template, or create their own—which they can save to use again later and share with others. The Template Library promotes greater standardization among data collectors by encouraging reuse of individual attributes and templates. Learn about the Observation Template Library on the NatureServe website (2014c).

Kestrel Online Observation Database: Supports Data Management, Integration, Mapping, and Sharing

Kestrel (NatureServe 2014a) is an online tool for biologists, researchers, and natural resource managers to map and manage observational data. Kestrel promotes greater standardization among observational datasets while allowing users to meet specific project needs.

Kestrel provides a secure, hosted environment for observational data management and sharing. It supports diverse observational data formats, all sharing a set of core attributes that minimally define an observation: what was seen, when, where, and by whom. Users can define the structure of the observation data they wish to collect and manage in Kestrel by modifying one of the existing templates published in the library or constructing a new template from scratch.

Through Kestrel's upload tool, users can quickly import and share data. To protect sensitive data, Kestrel allows survey data owners to restrict access by user, organization, or project at either the survey level or individual record level. For example, a state CMECS partner can create a survey to support local project data collection and share that survey and its associated observations within its restricted user group, whereas other partners can choose to share their surveys and observations with the entire CMECS community.

Kestrel uses an ArcGIS for Server–based mapping platform to manage observation locational data. Its multilingual interface supports English-, French-, and Spanish-speaking users. Kestrel uses web services to allow for integration with taxonomic sources to ensure consistent identification and naming of biodiversity elements across data collections and geographic jurisdictions. NatureServe is now implementing a CMECS taxonomy web service to integrate with Kestrel and support recording of observations against any standard CMECS classification unit.

Kestrel has tools to import and export observation data collections in spatial and tabular formats. Its mapping interface allows users to visualize observation locations in the spatial context of other mapped reference layers such as protected areas, shorelines, and species and habitat ranges. The

platform also allows users to output reports of observations by location, species or classification unit, date range, or observer and supports publishing to government data portals via web and map services.

Mobile Tools: Support Data Capture in the Field

Handheld data collection has been demonstrated to be faster and more accurate than paper-based methods (Spain et al. 2001). Increasingly, environmental data collected by instruments (e.g., satellites, buoy markers, remote monitoring stations) is being integrated into data collection methodology. Global Positioning System (GPS) units have vastly improved the ability of field workers to accurately georeference their observations. Similarly, portable computing devices—ranging from laptops and tablets to smartphones—enable field workers to record data directly in digital form, bypassing the need to transcribe field data. The observation toolkit’s mobile configuration software (NatureServe 2014b) is compatible with Windows Mobile GPS-enabled devices, such as the Trimble Juno, and integrates with ArcPad for field access to reference maps. Planned upgrades for the mobile tool component will expand support for more device types, including tablets. Smartphone applications are also possible, although their small screens may not be practical for entering complex data formats such as those associated with CMECS and similar ecological sampling survey designs.

Desktop Editor: Supports Offline Data Management, Validation, and Export

The ArcGIS for Desktop Editor toolkit supports offline data entry and analysis through a desktop editor. This tool can be useful for coastal and marine observation inventory and monitoring data collection protocols, which often involve the collection of large samples that are labeled and later assessed in the lab. The desktop editor supports data entry and staging; record cleanup; data aggregation, integration, and management; and export to Kestrel or other long-term storage databases. The desktop editor can also be used on a laptop in the field or at sea when Internet access is not available.

Crosswalking Tool: Utilities to Integrate Legacy Data

Many users seeking to implement CMECS want to integrate existing data into their analysis. In most cases, this data has been classified or attributed using systems other than CMECS and requires translation to the CMECS system for consistent query or analysis procedures. This process of translating data between classification systems is known as *crosswalking*. The first step of the crosswalking process is to establish the relationships between the units in the source classification and CMECS to develop a conceptual crosswalk (as described in appendix H in the CMECS documentation in FGDC [2012]).

Once the conceptual crosswalk has been established, users are ready to make the actual spatial data translation. The NOAA NOS Office for Coastal Management has developed a GIS tool to automate this conversion to CMECS as a way to facilitate the crosswalking process. This tool, which operates in an ArcMap environment as an ArcToolbox (.tbx) file, relies on look-up tables (LUTs) that articulate the source-to-CMECS unit relationships. A set of LUTs has been developed for some of the common classifications such as the Florida System for Classification of Habitats in Estuarine and Marine Environments (SCHEME) (Madley et al. 2002) and the Classification of Wetlands and Deepwater Habitats of the United States (FGDC 2013), but these can be modified by the user to adjust relationships or incorporate new classification systems. The tool allows input of Esri shapefile data (both point and polygon) and produces an output Esri File Geodatabase with multiple feature layers (by CMECS component).

Figures 4.4 to 4.7 illustrate how the spatial topology of the input data is preserved while separate component feature layers with CMECS attributes are produced as feature layers in an Esri geodatabase designed in advance by the user. The maps show source SCHEME data for Humboldt Bay, California, as a single polygon shapefile overlaying digital aerial imagery (figure 4.4) and output CMECS component feature layers for the biotic component (figure 4.5), substrate component (figure 4.6), and geofom component (figure 4.7). Transparent areas are null polygons.

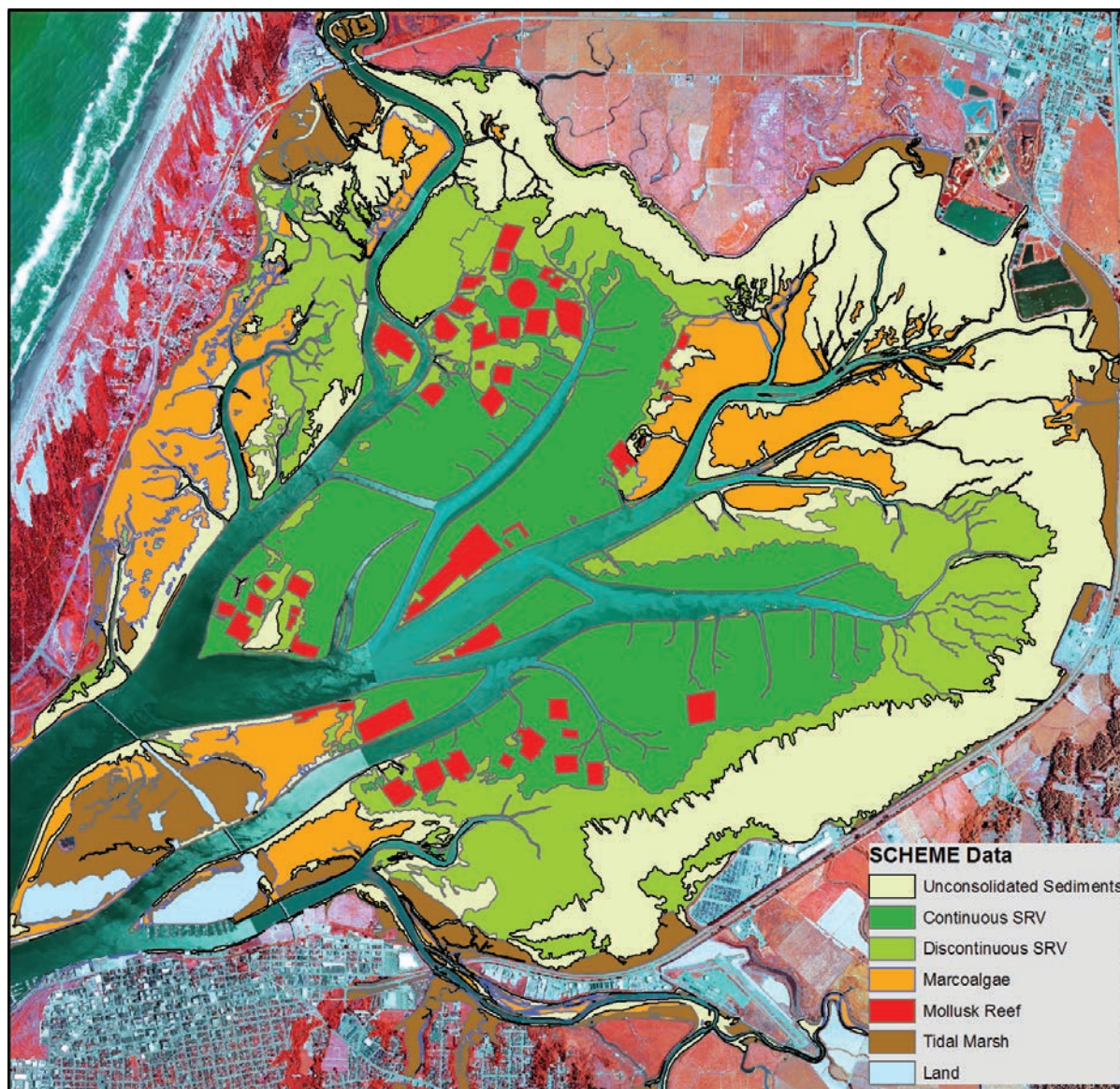


Figure 4.4. Florida System for Classification of Habitats in Estuarine and Marine Environments (SCHEME) input dataset in Esri shapefile format for Humboldt Bay used to produce separate Coastal and Marine Ecological Classification Standard component feature layers. Source imagery is digital mapping camera aerial imagery (false-color composite, bands 4, 3, 2) collected June 27, 2009. Resolution is ½ m pixels. Image collected at negative low-tide conditions. Overlying vector dataset is a Humboldt Bay, California, benthic cover dataset, developed by PhotoScience under contract to the NOAA NOS Office for Coastal Management, formerly the NOAA NOS Coastal Services Center. Classification is in Florida System for Classification of Habitats in Estuarine and Marine Environments (Madley et al. 2002). The minimum mapping unit is 100 sq mi minimum mapping unit. Datasets are in Esri shapefile format. Source for imagery and vector data: National Oceanic and Atmospheric Administration National Ocean Service Office for Coastal Management (2014). Courtesy of NOAA NOS Office for Coastal Management.

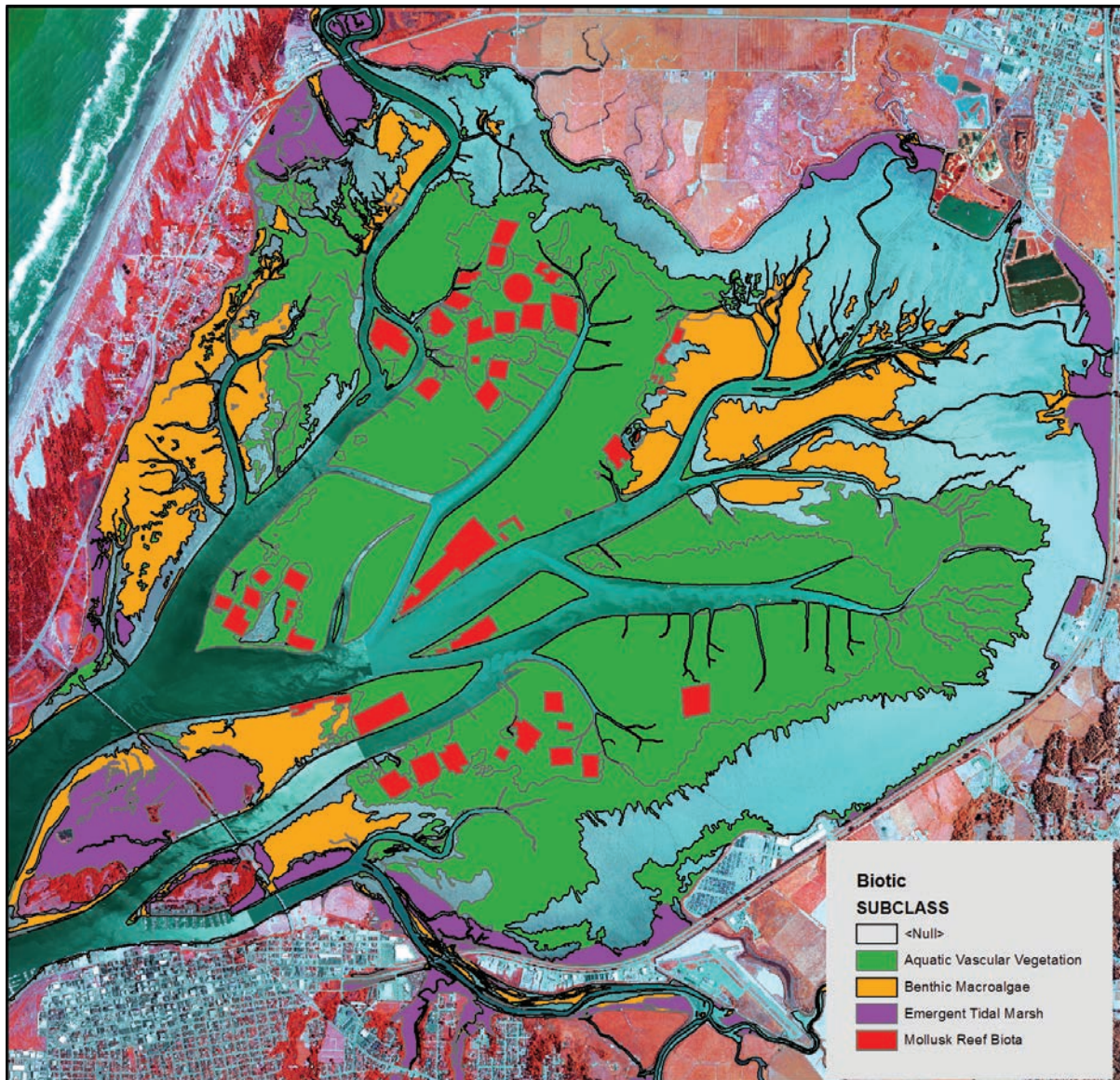


Figure 4.5. Florida System for Classification of Habitats in Estuarine and Marine Environments input dataset in Esri shapefile format for Humboldt Bay used to produce the biotic component feature layer output. Source imagery is digital mapping camera aerial imagery (false-color composite, bands 4, 3, 2) collected June 27, 2009. Resolution is ½ m pixels. Image collected at negative low-tide conditions. Overlying vector dataset is Coastal and Marine Ecological Classification Standard-compliant crosswalking tool output for the biotic component as a separate feature layer within the California Humboldt Bay geodatabase. Minimum mapping unit is the same as the source Florida System for Classification of Habitats in Estuarine and Marine Environments dataset. Clear (null) polygons are areas in which no automated crosswalking was possible between Florida System for Classification of Habitats in Estuarine and Marine Environments and Coastal and Marine Ecological Classification Standard biotic attributes. Source for imagery and vector data: National Oceanic and Atmospheric Administration National Ocean Service Office for Coastal Management (2014). Courtesy of NOAA NOS Office for Coastal Management.

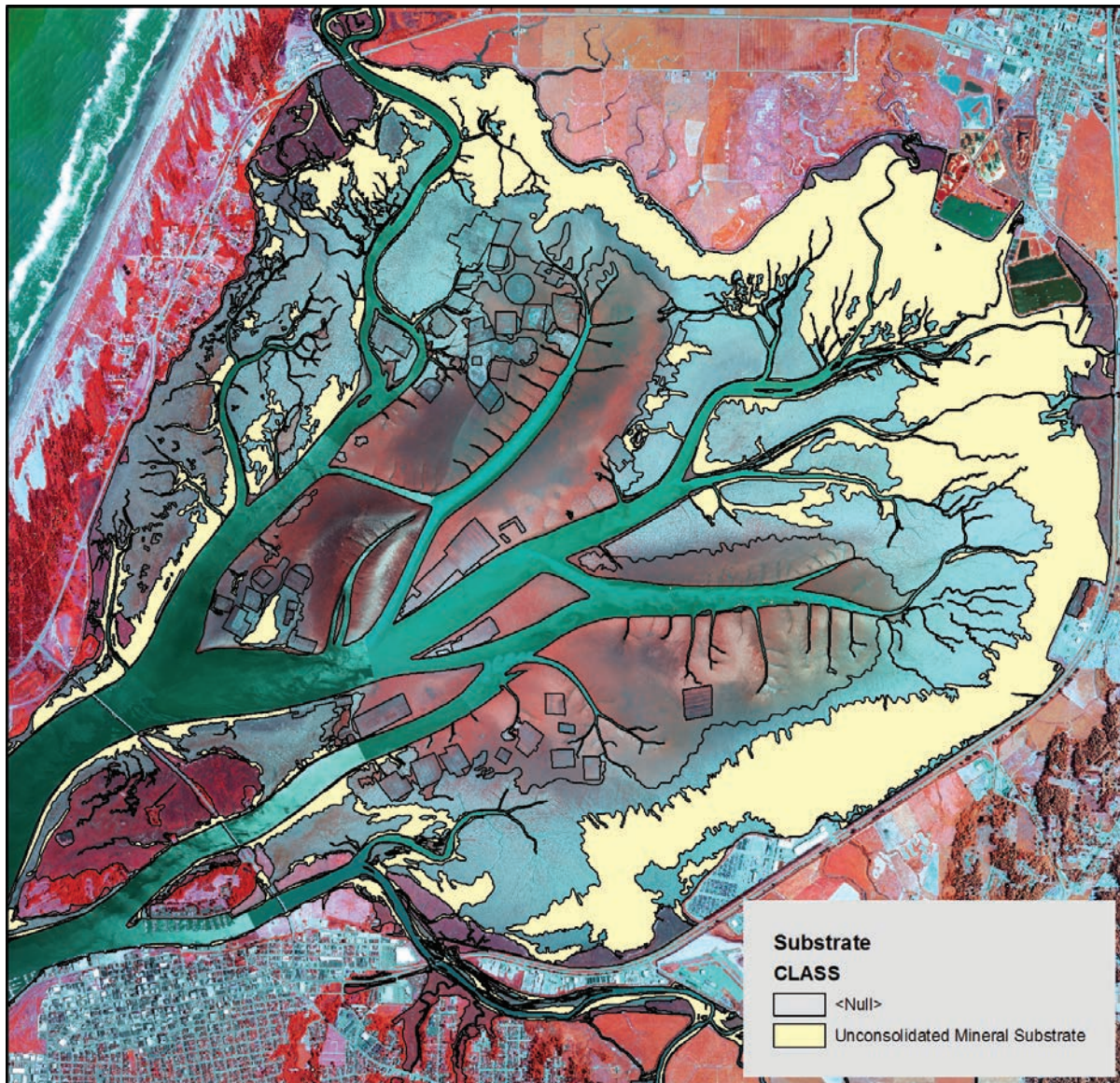


Figure 4.6. Florida System for Classification of Habitats in Estuarine and Marine Environments input dataset in Esri shapefile format for Humboldt Bay used to produce the substrate component feature layer output. Source imagery is digital mapping camera aerial imagery (false-color composite, bands 4, 3, 2) collected June 27, 2009. Resolution is ½ m pixels. Image collected at negative low-tide conditions. Overlying vector is Coastal and Marine Ecological Classification Standard-compliant crosswalking tool output for the substrate component as a separate feature layer within the California Humboldt Bay geodatabase. Minimum mapping unit is the same as the source Florida System for Classification of Habitats in Estuarine and Marine Environments dataset. Clear (null) polygons are areas in which no automated crosswalking was possible between Florida System for Classification of Habitats in Estuarine and Marine Environments and Coastal and Marine Ecological Classification Standard substrate attributes. Source for imagery and vector data: National Oceanic and Atmospheric Administration National Ocean Service Office for Coastal Management (2014). Courtesy of NOAA NOS Office for Coastal Management.

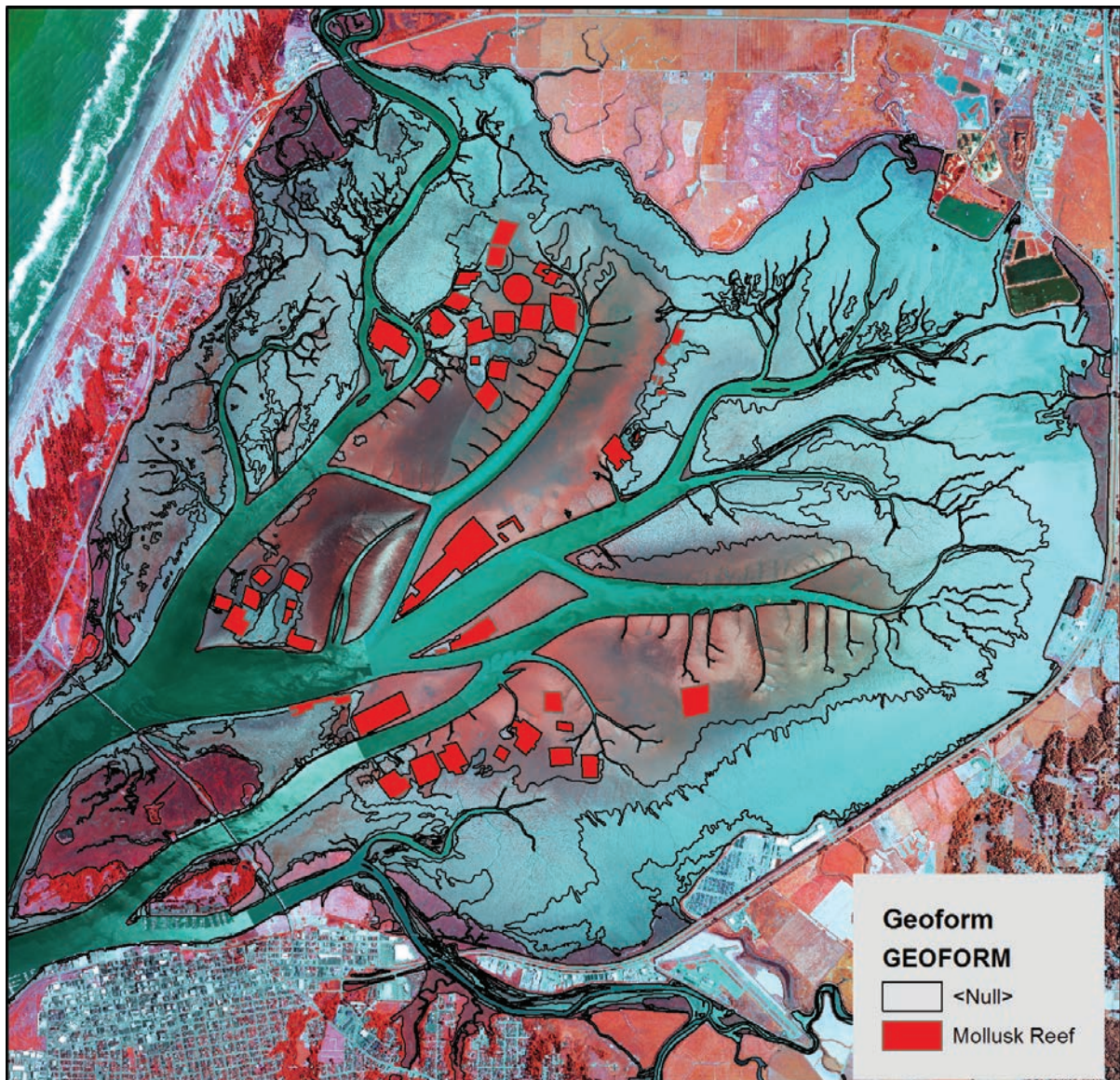


Figure 4.7. Florida System for Classification of Habitats in Estuarine and Marine Environments input dataset in Esri shapefile format for Humboldt Bay used to produce the geoform component feature layer output. Source imagery is digital mapping camera aerial imagery (false-color composite, bands 4, 3, 2) collected June 27, 2009. Resolution is ½ m pixels. Image collected at negative low-tide conditions. Overlying vector is Coastal and Marine Ecological Classification Standard-compliant crosswalking tool output for the geoform component as a separate feature layer within the California Humboldt Bay geodatabase. Minimum mapping unit is the same as the source Florida System for Classification of Habitats in Estuarine and Marine Environments dataset. Clear (null) polygons are areas in which no automated crosswalking was possible between Florida System for Classification of Habitats in Estuarine and Marine Environments and Coastal and Marine Ecological Classification Standard geoform attributes. Source for imagery and vector data: National Oceanic and Atmospheric Administration National Ocean Service Office for Coastal Management (2014). Courtesy of NOAA NOS Office for Coastal Management.

The crosswalking tool does not attempt to assign CMECS output values for those features that do not have CMECS-equivalent units or for which the confidence in an automated process might be low. Rather, it preserves the original feature with a null value, which the user can then attribute through a more individualized process. By allowing the user to modify LUTs, test runs of the tool can be made to assure that the resulting spatial data meets expectations. Efforts are under way to provide lists of choices for potential equivalent CMECS units as a way to guide the user in conducting the crosswalking. The output attribute table produced by this tool draws on the CMECS code set and integrates with the NatureServe observation toolkit. This tool helps establish consistency in data translation and processing of large amounts of data. Once the crosswalking tool has been used to translate mapped, nonstandard observations to CMECS, the legacy data can be integrated with other CMECS-compliant data in Kestrel.

Case Study

Implementation of the observation toolkit by Parks Canada provides a case study of how the toolkit can be used to collect and manage new observation data and integrate it with existing data to inform decision-making. In this case, Parks Canada had to manage biodiversity information to meet its mandate to “protect and present significant examples of Canada’s natural and cultural heritage” and help it implement and enforce the Species at Risk Act (SARA) (Oliver 2004).

Parks Canada had the objective of standardizing new species observation data collections across a network of parks with many observers and integrating the new data with volumes of legacy species observation data that was collected over many years using multiple standards in parks throughout Canada. The observation toolkit helped Parks Canada compile a standardized, comprehensive observation dataset on at-risk species in its parks.

Parks Canada adopted the standard species taxonomy employed and managed by NatureServe and its network of provincial conservation data centers, which is a compilation of taxonomic concepts derived from multiple authoritative species groups throughout North America. Using the Template Library, Parks Canada designed data templates to standardize new observation data collected by the parks. The templates included the core data model fields for Species, Location, Observation Date, and Primary Observer, as well as additional data fields needed for each type of survey (e.g., Critical Habitat). The templates also supported customization to allow for park-specific data for the park managers. Templates were also designed to crosswalk, validate, and integrate legacy data within the shared Kestrel data management platform.

Species observations created or uploaded in Kestrel were linked to the standard taxonomy via web services to provide all users access to the standard species names. The Kestrel observation database was made available to parks throughout Canada. This database is regularly updated with new observations and is used to identify critical habitat for at-risk species within the parks to help Parks Canada plan for their management and protection. Although this case focuses on species data in both marine and terrestrial environments, the basic steps and tools for implementation are analogous to those that can be employed for the collection and integration of marine ecosystem observation data.

Conclusion

The need for marine biodiversity observation data to guide resource management and conservation decision-making is receiving increasing recognition; and many national, regional, and local efforts are under way to produce this data. In the United States, NOAA, USGS, and the National Aeronautics

and Space Administration are leading a new initiative to create a national Marine Biodiversity Observation Network (MBON); and MBONs are already in place in Europe, Asia-Pacific, and the Arctic (National Oceanographic Partnership Program 2010; Duffy et al. 2013). The US National Park Service has recently called for the production of nearshore ecosystem maps to help managers understand the impacts of Hurricane Sandy, and efforts are under way to create a regional habitat map for the Northwest Atlantic. The State of Oregon is also currently remapping its coastal ecosystem. All these efforts call for the need to develop new observations of ecosystems, and most call for integrating the new data with legacy data. All are proposing to use CMECS as the classification standard.

NatureServe's observation toolkit and NOAA's crosswalking tool can support these and future efforts to collect, upload, validate, aggregate, integrate, share, and publish marine ecosystem observation data. The toolkit will provide direct online access to data collection protocols and tools across the growing community of CMECS users and promote easier adoption of the standard. The data templates, online observation database platform, and associated quality control utilities will enforce consistent application of the standard and support the integration of new and legacy data inputs to allow more meaningful information outputs, while allowing flexibility for users to enter data beyond what is required for the standard.

Acknowledgments

The comments and suggestions of two anonymous reviewers greatly improved this chapter.

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CHAPTER 5

How Does Climate Change Affect Our Oceans?

Peter Kouwenhoven, Yinpeng Li, and Peter Urich

Abstract

Global climate change not only affects terrestrial ecosystems, but it also has profound consequences for the oceans. The latest results of the numerical models that were run for the *Fifth Assessment Report of the Intergovernmental Panel on Climate Change* include many ocean variables. The outputs of these models are difficult to access, assess, use, and interpret. This chapter seeks to transform these outputs into more usable and useful results via global maps that highlight the changes in specific oceanographic variables by the year 2050. It describes the methodology for extracting the relevant information from the models and looks at the consequences for selected ocean variables under projected climate change. These variables include pH (which is relevant to the survival of coral reefs) and net primary production (which forms the base of the entire oceanic food chain and is also relevant to eutrophication issues in coastal areas). In addition, the use of the SimCLIM for ArcGIS/ Marine add-in for ArcGIS for Desktop software enabled the creation of global output variables for the ArcGIS platform. The results lend insight as to what might happen in the oceans as a result of climate change, and may thus inform priorities in current and future research as well as policy making.

Introduction

The environment is changing on a global scale as the result of changes in the atmospheric concentrations of carbon dioxide (CO₂) and other greenhouse gases caused directly by anthropogenic emissions and changes in land use, and indirectly by processes such as the melting of the permafrost, which releases methane. This increase in atmospheric concentrations causes an increase in air temperatures, commonly referred to as *global warming*, or more generically, *global climate change*. There is no longer any doubt that human activities are accelerating the change (IPCC 2013). It is increasingly being realized that climate change not only affects terrestrial ecosystems, but also has a profound effect on the oceans. And the effect is even more profound as many of the ocean's biogeochemical cycles and ecosystems are being increasingly stressed by at least three factors driven by climate change: *rising temperatures*, *ocean acidification*, and *ocean deoxygenation*. Each of these variables can cause substantial change in the physical, chemical, and biological environment, affecting the ocean's biogeochemical cycles and ecosystems in ways that we are only beginning to fathom (Gruber 2011; Doney et al. 2012; Bopp et al. 2013).

Ocean warming is the result of the heat transfer between the warming air and the ocean's surface. It affects organisms and biogeochemical cycles directly as well as through an increase of upper-ocean stratification.

Ocean acidification results from the fact that about one-quarter of the anthropogenic CO₂ emissions dissolve in the ocean, making it more acidic (Mora et al. 2013). The changes in the ocean's carbonate chemistry induced by this uptake negatively affect many organisms and processes, including shellfish, phytoplankton, and most profoundly, coral reefs.

Ocean deoxygenation is the decrease of dissolved oxygen levels in the ocean. It is bound to occur in a warming ocean and is exacerbated by stratification, causing stress to macroorganisms that depend critically on sufficient levels of oxygen.

These three stressors—warming, acidification, and deoxygenation—operate globally, but with distinct regional differences. The impacts of ocean acidification tend to be strongest in the high latitudes, whereas the already low-oxygen regions around the equator are most vulnerable to climate change–induced deoxygenation. Specific regions, such as the eastern boundary upwelling systems, are strongly affected by all three stressors, making them potential hot spots for impacts from climate change. Of additional concern are synergistic effects such as ocean acidification–induced changes in the type and magnitude of the organic matter exported to the ocean's interior, which then might cause substantial changes in the oxygen concentration there. Ocean warming, acidification, and deoxygenation are mostly irreversible on decadal time scales (Andrews et al. 2013). Once these changes set in, it will take centuries for the oceans to recover. With the emissions of CO₂ as the primary driver of all three stressors, the global strategy should be to reduce these emissions through mitigation, and offset them through sequestration. Considering that global deforestation accounts for one-third of the increase in atmospheric CO₂ levels (IPCC 2013), reforestation looks to be a most important strategy.

Natural resource management must also remain flexible to absorb the sudden and nonlinear changes that are likely to characterize the behavior of most ecosystems in the future. Overall, however, reducing greenhouse gas emissions remains the priority, not only because it will reduce the huge costs of adaptation but also because it will reduce the growing risk of pushing our planet into an unknown and highly dangerous state (Hoegh-Guldberg and Bruno 2010).

The numerical models used to project the effects induced by changes in atmospheric greenhouse gases produce outputs that are difficult to access, assess, use, and interpret. This chapter seeks to transform these outputs into more usable and useful results, via global maps that highlight the changes in specific oceanographic variables by 2050.

Methodology

The Intergovernmental Panel on Climate Change (IPCC) produces reports on the effects and impacts of climate change. The most recent set of reports is referred to as the *Fifth Assessment Report* (AR5), Working Group I, chapter 6 for “Carbon and Other Biogeochemical Cycles” (Ciais et al. 2013) and chapter 12 for “Long-Term Climate Change: Projections” (Collins et al. 2013), and is based on multiple model runs of generalized circulation models or global climate models (GCMs). Detailed results of these models are released through the Climate Models Intercomparison Program (CMIP), which has now reached its fifth cycle, or CMIP5 (World Climate Research Programme 2011; Taylor et al. 2012).

Some GCMs contain ocean biogeochemical models that are mathematical representations of the interactions between chemical and biological components of an ecosystem. Ocean biogeochemical models (Gettelman et al. 2012) (figure 5.1) can be used to study the dynamics between dissolved gases (e.g., oxygen and CO₂) and inorganic nutrients (e.g., phosphate and nitrate), as well as the lower trophic levels of the ecosystem (e.g., bacteria to plankton). The biogeochemical models

can be linked with hydrodynamic models and higher trophic-level models to give a mathematical representation of the whole ecosystem (Le Quéré et al. 2005; Fennel 2009).

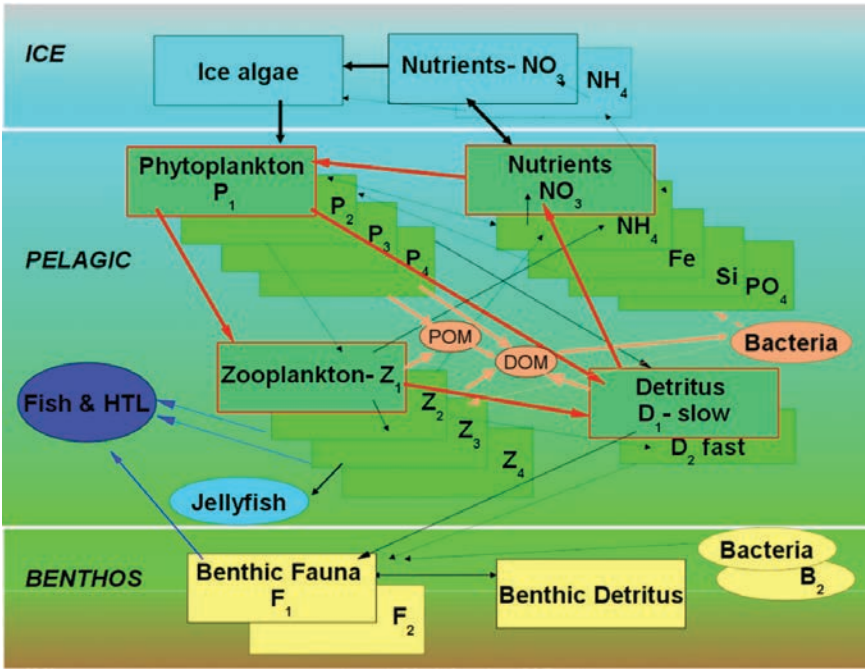


Figure 5.1. A simple nutrient, phytoplankton, zooplankton, detritus model.

As GCMs by definition project future climate, assumptions can be made about future greenhouse gas emissions. AR5 introduced the concept of representative concentration pathways (RCPs). The four greenhouse gas concentration (not emissions) trajectories are RCP2.6, RCP4.5, RCP6.0, and RCP8.5, named after a possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6.0, and 8.5 W/m² respectively) (table 5.1).

Table 5.1. Overview of Representative Concentration Pathways (Moss et al. 2010; Van Vuuren et al. 2007; Rogelj et al. 2012)

Description*		CO ₂ Equivalent	SRES Equivalent
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m ² in 2100.	1370	A1FI
RCP6.0	Stabilization without overshoot pathway to 6 W/m ² at 2100.	850	B2
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m ² 2100.	650	B1
RCP2.6	Peak in radiative forcing at ~ 3 W/m ² before 2100 and decline.	490	None

*Approximate radiative forcing levels were defined as $\pm 5\%$ of the stated level in W/m² relative to preindustrial levels. Radiative forcing values include the net effect of all anthropogenic greenhouse gases and other forcing agents.

From the GCMs (see table 5.2), monthly outputs for selected ocean biogeochemical variables were processed to determine the global area weighted mean for each year from 2006 to 2100 for all the available GCMs' RCP runs. To determine a global average change per variable (GV), the GCM

ensemble mean of each RCP was calculated. Finally, the 95-year values were fitted to smooth, curved polynomial lines. The difference between 1995 and a projection year is called ΔGV . Figure 5.2 shows sea surface temperature (SST) as an example of one of the selected ocean biogeochemical variables. In the pattern-scaling approach that is used, the global curves are essential information as local changes are expressed per global change (i.e., local SST changes $X^{\circ}\text{C}$ per 1°C of change in global average SST).

Table 5.2. Variables Available per Global Climate Model

GCM name	DfE	INTPP	NO ₃	O ₂	PH	PO ₄	SI	SST	TALK
ACCESS1-0								X	
ACCESS1-3								X	
CANESM2		X	X		X			X	X
CCSM4								X	
CESM1-BGC	X	X	X	X	X	X	X	X	X
CESM1-CAM5								X	
CESM1-CAM5								X	
CNRM-CM5	X	X	X	X		X	X	X	X
CSIRO-MK3-6-0								X	
EC-EARTH								X	
GFDL-CM3								X	
GFDL-ESM2G	X	X	X	X	X	X	X	X	X
GFDL-ESM2M	X	X	X	X	X	X	X	X	X
GISS-E2-H								X	
GISS-E2-R								X	
HADGEM2-AO								X	
HADGEM2-CC	X	X	X	X	X		X	X	X
HADGEM2-ES	X	X	X	X	X		X	X	X
INMCM4								X	
IPSL-CM5A-LR	X	X	X	X	X	X	X	X	X
IPSL-CM5A-MR	X	X	X	X	X	X	X	X	X
IPSL-CM5B-LR	X	X	X	X	X	X	X	X	X
MIROC5								X	
MPI-ESM-LR	X	X	X	X	X	X	X	X	X
MPI-ESM-MR	X	X	X	X	X	X	X		X
MRI-CGCM3								X	
NORES1-M								X	
NORES1-ME	X	X	X	X	X	X	X		X

DfE: dissolved iron concentration at surface ($\mu\text{mol}/\text{m}^3$)

INTPP: net primary productivity of carbon by phytoplankton ($\text{gC}/\text{m}^2/\text{day}$)

NO₃: dissolved nitrate concentration at surface (mmol/m^3)

O₂: dissolved oxygen concentration at surface (unit: mol/m^3)

PH: pH at surface (no unit)

PO₄: dissolved phosphate concentration at surface (mmol/m^3)

SI: dissolved silicate concentration at surface (mmol/m^3)

SST: sea surface temperature ($^{\circ}\text{C}$)

TALK: total alkalinity at surface (mol/m^3)

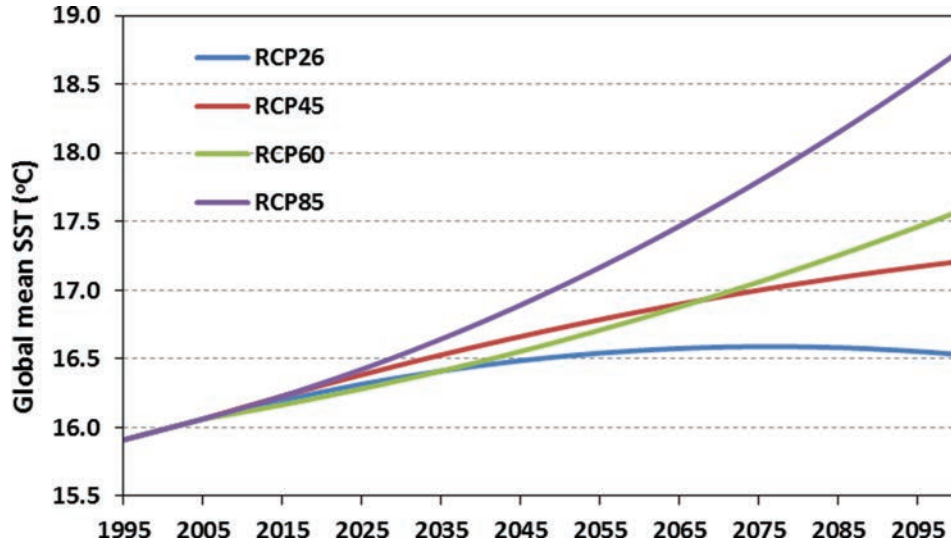


Figure 5.2. Global curves for sea surface temperature calculated from representative concentration pathways 2.6, 4.5, 6.0, and 8.5.

For a given climate variable V , its anomaly ΔV^* for a particular grid cell (i), month (j), and year or period (y) under an RCP is

$$\Delta V_{yij}^* = \Delta GV_y \cdot \Delta V'_{ij}, \quad (5.1)$$

where ΔGV is the annual global mean change of variable V .

The local change pattern value ($\Delta V'_{ij}$) was calculated from the GCM simulation anomaly (ΔV_{yij}), using linear least squares regression—that is, the slope of the fitted linear line, as

$$V'_{ij} = \frac{\sum_{y=1}^m GV_y \cdot V_{yij}}{\sum_{y=1}^m (GV_y)^2}, \quad (5.2)$$

where m is the number of future sample periods used, with a five-year average as a period and with 19 periods from 2006 to 2100.

The SimCLIM for ArcGIS/Marine toolbar add-in made the global curves and local change patterns operational in ArcGIS for analyzing the effects of projected changes in climate on ocean variables. For a selected variable, RCP, and projection year, equation (5.1) calculates the changes between the baseline period and projection year.

Baselines for the various variables were constructed using different data sources:

- Dissolved nitrate concentration at surface, dissolved oxygen concentration at surface, dissolved phosphate concentration at surface, and dissolved silicate concentration at surface are used in the World Ocean Atlas (WOA) (National Oceanographic Data Center 2010).
- The SST baseline was constructed from the Hadley Centre Sea Ice and SST dataset (Met Office Hadley Centre for Climate Change 2009) using the mean of the 1981–2010 data.
- For the remaining variables (dissolved iron concentration at surface, net primary productivity at surface, pH at surface, and total alkalinity at surface), the ensemble mean of 1985–2005 GCM historical runs was used.

All the baseline and change patterns were spatially interpolated from the GCM original resolutions to a finer $0.25^\circ \times 0.25^\circ$ grid using a bilinear interpolation method.

Not all the GCMs have ocean biogeochemical components, and not every model has all the RCP experiments. Moreover, sometimes data quality issues arise, such as missing data. Table 5.2 lists the variables that are available per GCM.

The analysis focused on the differences between the baseline situation (2006) and climate-changed situation in 2050. The global atmosphere is currently close to 400 ppm CO₂ equivalents, and concentrations of CO₂ and non-CO₂ gases are increasing at a rate that is of concern (Prinn 2013). To demonstrate maximum impacts, the RCP8.5 emission pathway was selected in the SimCLIM for ArcGIS/Marine tool, and a scenario was generated. For each scenario, the median value of the full set of GCMs was used (with the actual set varying per variable, depending on availability). All results focused on annual averages (from monthly data), except for SST which focused on the warmest month.

Results

Sea Surface Temperature

SST is relevant for warm-water corals. At certain levels, it can trigger a coral-bleaching event. Figure 5.3 shows the contour lines for SST for the baseline year (black) and 2050 (red), for the warmest month, which can be a different month for different locations (e.g., the Northern versus the Southern Hemisphere). As the temperatures around 28°C to 31°C can trigger coral-bleaching episodes, only these contours are shown. A considerable expansion of the area at risk is clearly visible, with core coral zones reaching temperatures of over 31°C, thus endangering all warm-water corals.

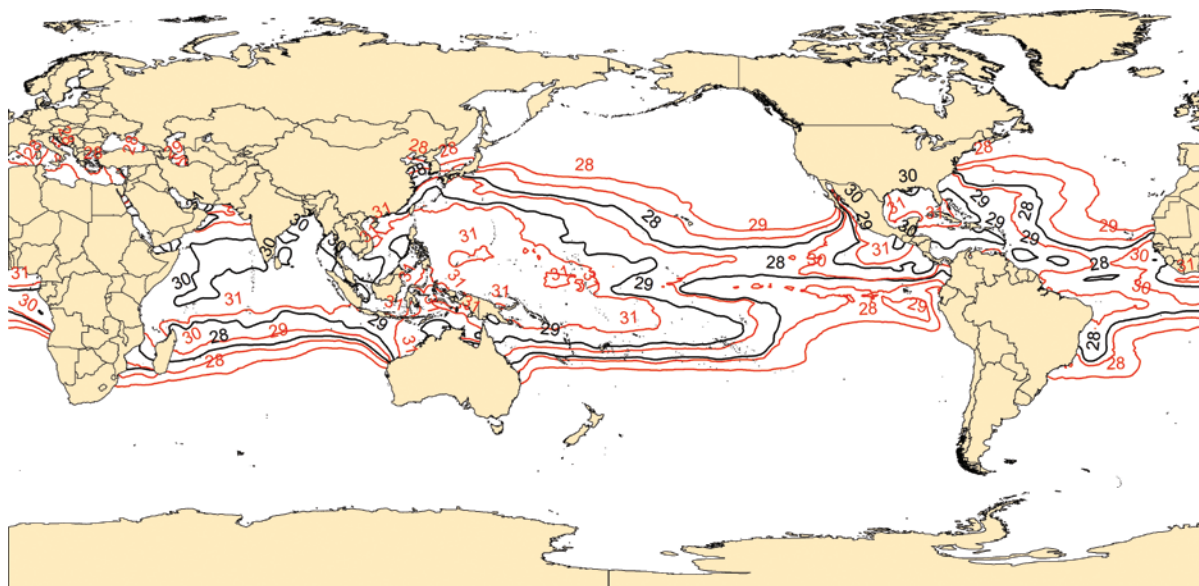


Figure 5.3. Sea surface temperature contours for 2006 (black) and 2050 (red) under representative concentration pathway 8.5. Data from CLIMsystems.

Net Primary Productivity of Carbon by Phytoplankton

The change in net primary production is presented in figure 5.4 as a percentage change ($\Delta\%$) from the baseline (units of gC/m³/day, see table 5.2). The bluish areas show a decrease (of up to -10%) in net primary production, while the yellow/orange/red areas indicate an increase (of up to 10%). The

results show a decrease in primary production over much of the global ocean, with the exception of parts of the southern ocean and the Arctic which have an increasing trend because of the strong increase in temperatures in these regions. Figure 5.5 shows the global average change in primary production.

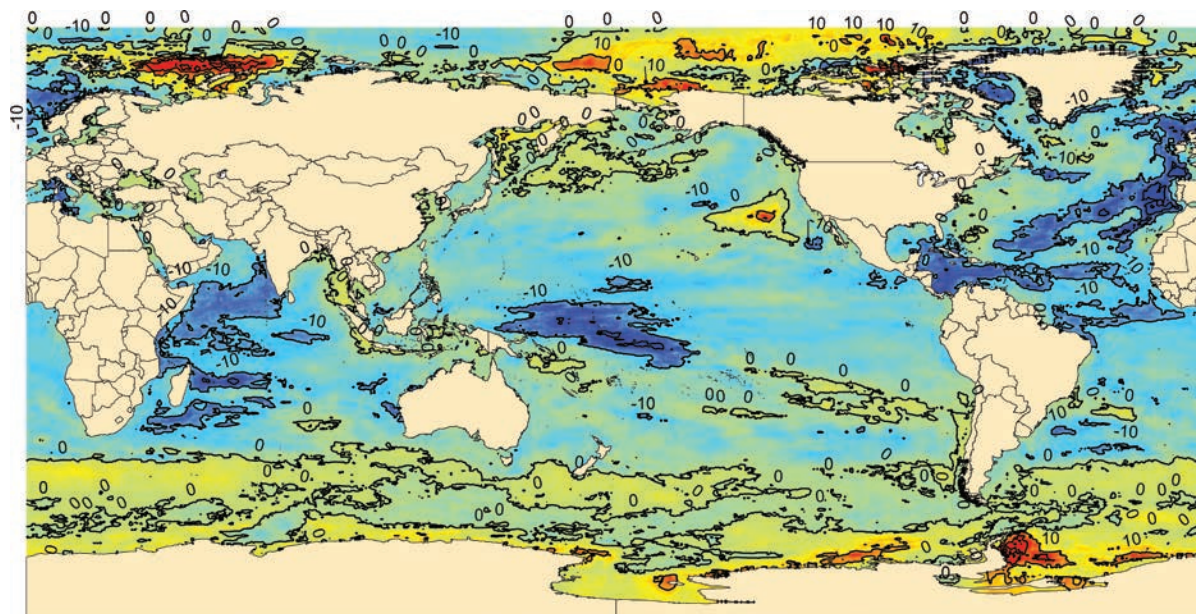


Figure 5.4. Color contour map shows the percentage change in net primary production between 2006 and 2050 under representative concentration pathway 8.5 (largest decreases up to 10% shown in blue, largest increases up to 10% shown in red). Data from CLIMsystems.

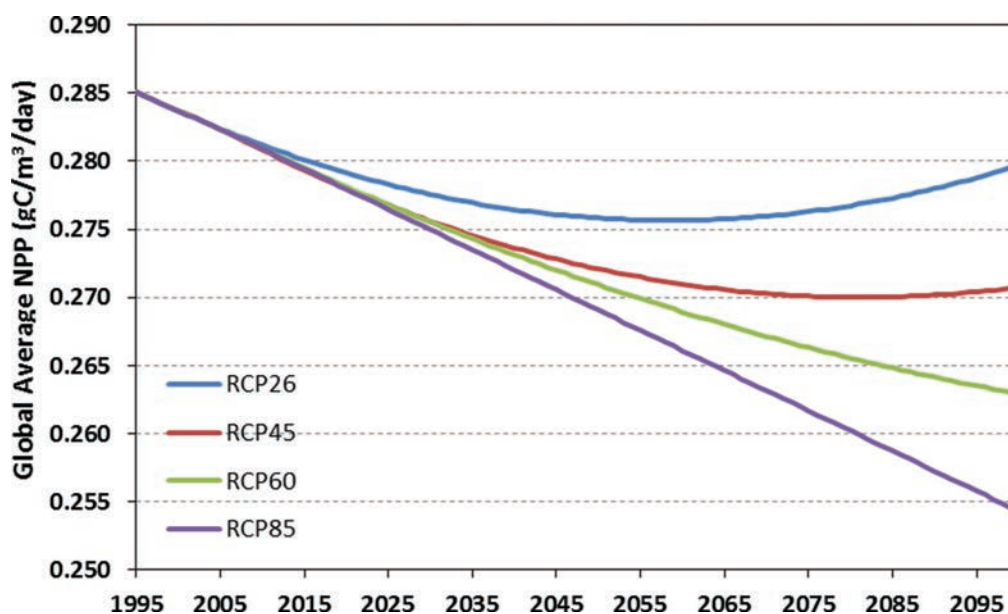


Figure 5.5. Global average change in primary production calculated from representative concentration pathways 2.6, 4.5, 6.0, and 8.5. Data from CLIMsystems.

Dissolved Oxygen Concentration at Surface

Figure 5.6 shows that changes in dissolved oxygen concentration ($\Delta\%$ from the baseline) are small (less than 3%) and negative for all oceans. The strongest decrease (-5%) is in the red areas, which coincide with important fishing grounds, prompting changes in management of these areas.

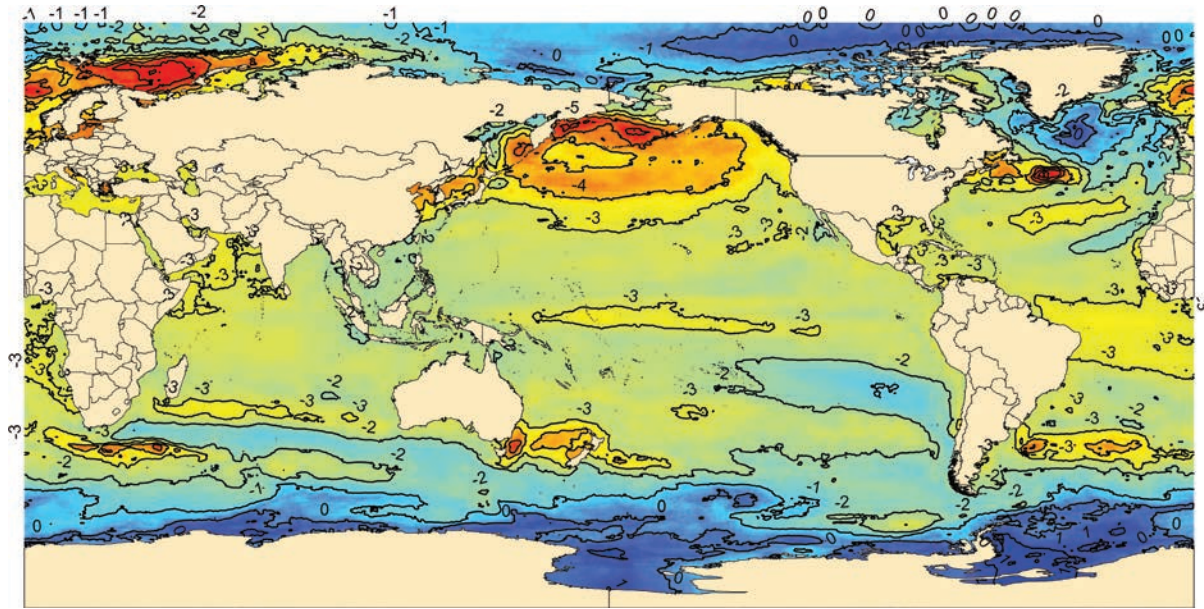


Figure 5.6. Color contour map shows the percentage change in dissolved oxygen between 2006 and 2050 under representative concentration pathway 8.5 (largest decreases in red, no change or small increases in blue). Data from CLIMsystems.

Ocean pH and Total Alkalinity

Ocean acidification has a critical effect on coral reefs. Coral reefs are highly productive and biologically diverse ecosystems that are either showing signs of deterioration or undergoing community structure changes because of a host of anthropogenic and natural factors. These factors include bleaching, resource depletion, changing sedimentation rates and turbidity, eutrophication, cyclone damage, and natural climate variability such as El Niño Southern Oscillation. In addition to these environmental pressures, the ability of coral reefs to calcify, produce calcium carbonate (CaCO_3), and provide framework structures as habitat may also be adversely affected by the oceanic uptake of anthropogenic CO_2 (Sabine et al. 2004) and gradual ocean acidification.

Changes in temperature, oxygen content, and other ocean biogeochemical properties directly affect the ecophysiology of water-breathing organisms. Previous studies (Edwards and Richardson 2005; Perry et al. 2005; Dulvy et al. 2008; Cheung et al. 2009; Cheung et al. 2010; Genner et al. 2010) suggest that the most prominent biological responses are changes in distribution, phenology, and productivity. Both theory and empirical observations also support the hypothesis that warming and reduced oxygen will reduce the body size of ocean fishes. The assemblage-averaged maximum body weight is expected to shrink by 14% to 24% globally from 2000 to 2050 under a high-emission

scenario. About half of this shrinkage is because of change in distribution and abundance, with the remainder from changes in physiology. The tropical and intermediate latitudinal areas will be heavily impacted, with an average reduction of more than 20%.

Acidification-driven changes in carbonate chemistry can cause diverse physiological responses among organisms. Organisms vary in their response to acidification; negative effects are evident, particularly among calcifying (shell-building) species. The process of shell formation and maintenance in ocean organisms is vulnerable to acidification. Co-occurring environmental stressors can modify or exacerbate the effects of acidification.

Biological processes influence seawater chemistry: for example, photosynthesis and respiration can influence pH on a day and night basis and over longer periods. The processes also contribute to carbon cycling in the ocean.

Biological adaptation to ocean acidification conditions has been demonstrated for some species, but the current rate of acidification is unprecedented over the past 300 million years (Hoenisch et al. 2012). Indeed, similar past events have been accompanied by major extinctions of ocean organisms.

Because pH is a nonlinear variable, the difference between the 2050 situation and baseline is presented in figure 5.7 in absolute units. Because about one-quarter of the global carbon emissions dissolve in the oceans, it makes them slightly more acidic, decreasing the pH. There is also an impact from the increase in temperature, which is biggest in the Arctic area. The small shift of around -0.18° is enough to cause major problems for coral reefs.

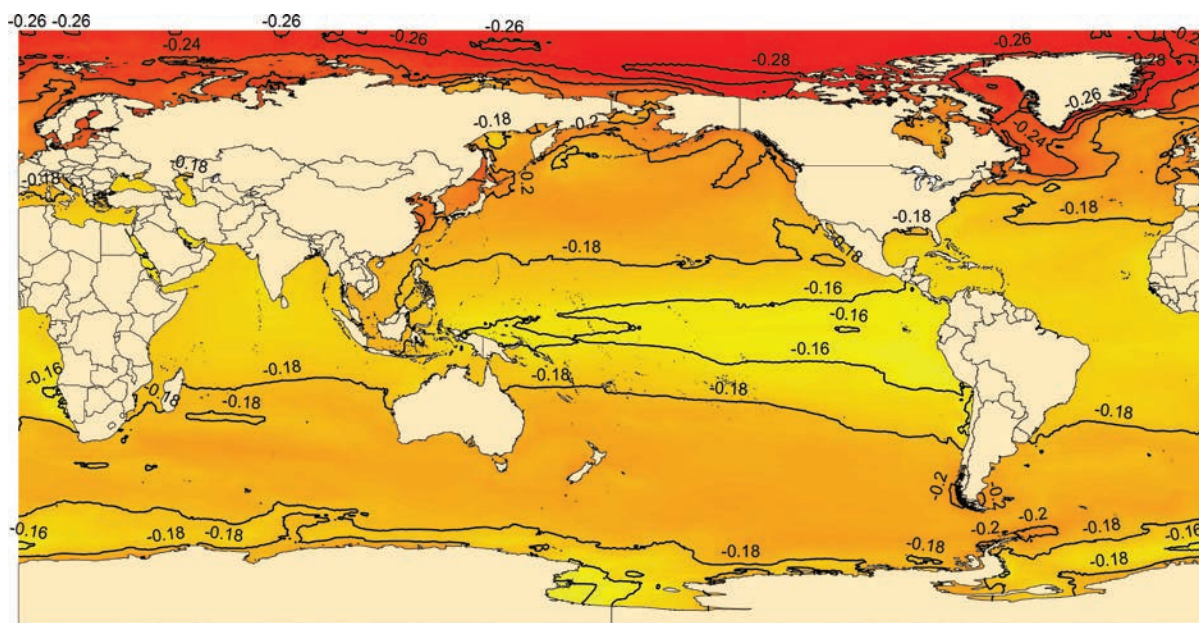


Figure 5.7. Color contour map shows the percentage change in pH between 2006 and 2050 under representative concentration pathway 8.5 (largest decreases in pH or more acidic conditions in *red*, no change or smallest decreases in pH in *yellow*). Data from CLIMsystems.

Another way to show the effects of ocean acidification is through the total alkalinity at the surface. Figure 5.8 shows that the $\Delta\%$ in total alkalinity is very small, less than 0.4% (down in the blue areas, up in the purple), but still shows broad regional increases for areas such as the Gulf of Mexico and western part of the northern Atlantic.

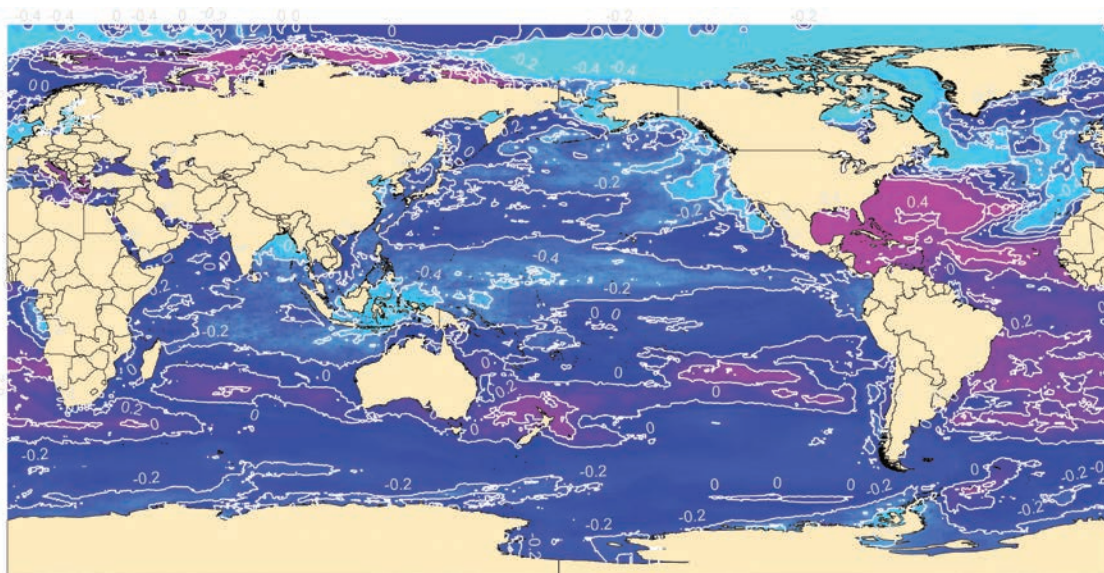


Figure 5.8. Color contour map shows the percentage change in total alkalinity between 2006 and 2050 under representative concentration pathway 8.5 (largest increase in total alkalinity in purple, no change or smallest decrease in dark blue). Data from CLIMsystems.

Dissolved Nitrate Concentration at Surface

Nitrification is a central process in the nitrogen cycle that produces both the greenhouse gas (GHG) nitrous oxide and oxidized forms of nitrogen used by phytoplankton and other microorganisms. As anthropogenic CO₂ invades the ocean, pH-driven reductions in ammonia oxidation rates could fundamentally change how nitrogen is cycled and used by organisms in the sea. Figure 5.9 shows the $\Delta\%$ from the baseline in nitrate concentrations. Because many areas have very low concentrations, small absolute changes translate into large and critical relative changes. With some exceptions (red areas), nitrate concentrations are projected to decrease across most oceans.

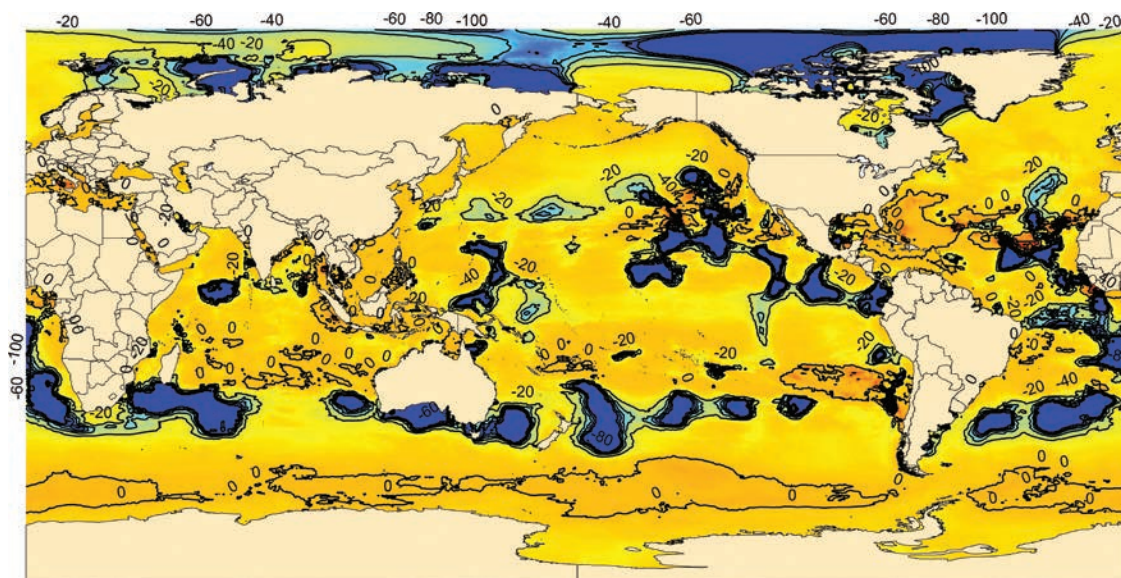


Figure 5.9. Color contour map shows the percentage change in dissolved nitrate between 2006 and 2050 under representative concentration pathway 8.5 (largest decrease in dissolved nitrate in dark blue, no change or smallest increases in orange and red). Data from CLIMsystems.

Dissolved Phosphate, Silicate, and Iron at Surface

Figure 5.10 shows that the concentration of dissolved phosphate is decreasing everywhere, marginally (0% to 10%) in most oceans (red), with dispersed exceptions showing a decrease of up to 60% (blue). Dissolved phosphate and silicate are both important nutrients in the oceans, and thus can have an important impact on primary productivity, as well as the distribution of species and structure of ecosystems. In some parts of the ocean, they are more critical than dissolved nitrogen or dissolved iron as a limiting factor, and thus are becoming more widely recognized as studies of phosphate in the oceans expands (Paytan and McLaughlin 2006).

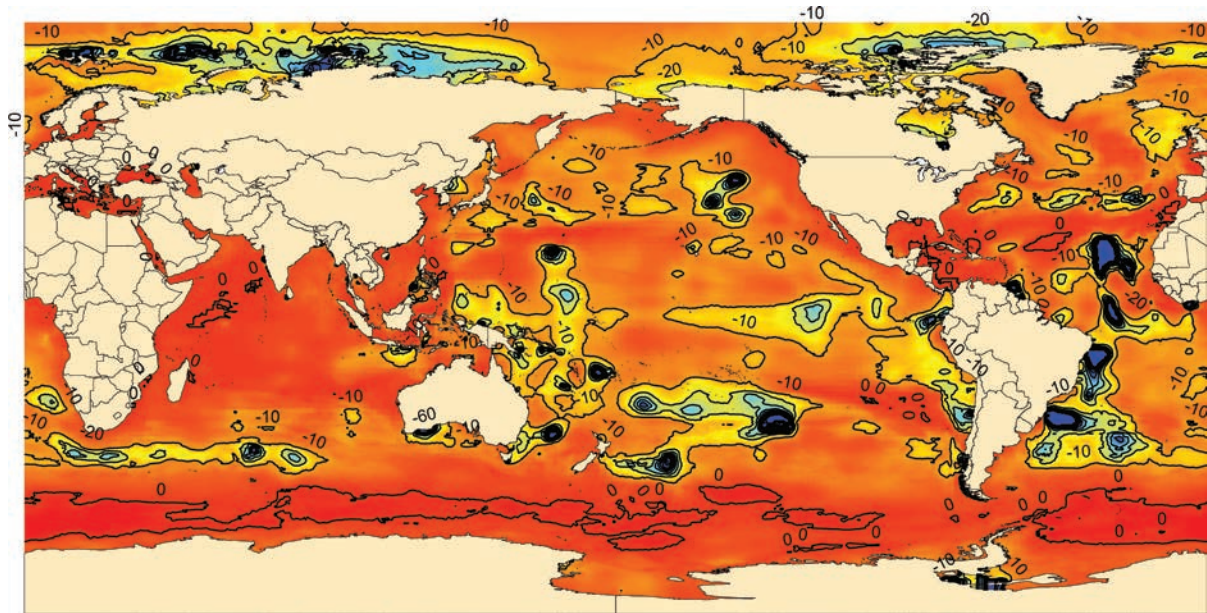


Figure 5.10. Color contour map shows the percentage change in dissolved phosphate between 2006 and 2050 under representative concentration pathway 8.5 (decreases in dissolved phosphate of 0% to 10% in red, largest decreases up to 60% in blue). Data from CLIMsystems.

Iron, along with nitrogen, is one of the better understood elements in the ocean, and it is recognized as a limiting factor over wider areas than phosphate. Figure 5.11 shows that dissolved iron concentration at the surface remains about the same (blue) or at an increase of up to 30% in specific hot spots (red). Conversely, figure 5.12 shows an overall decrease in silicate concentrations of 0% to 20%, but in some areas (red) the decrease is 50%.

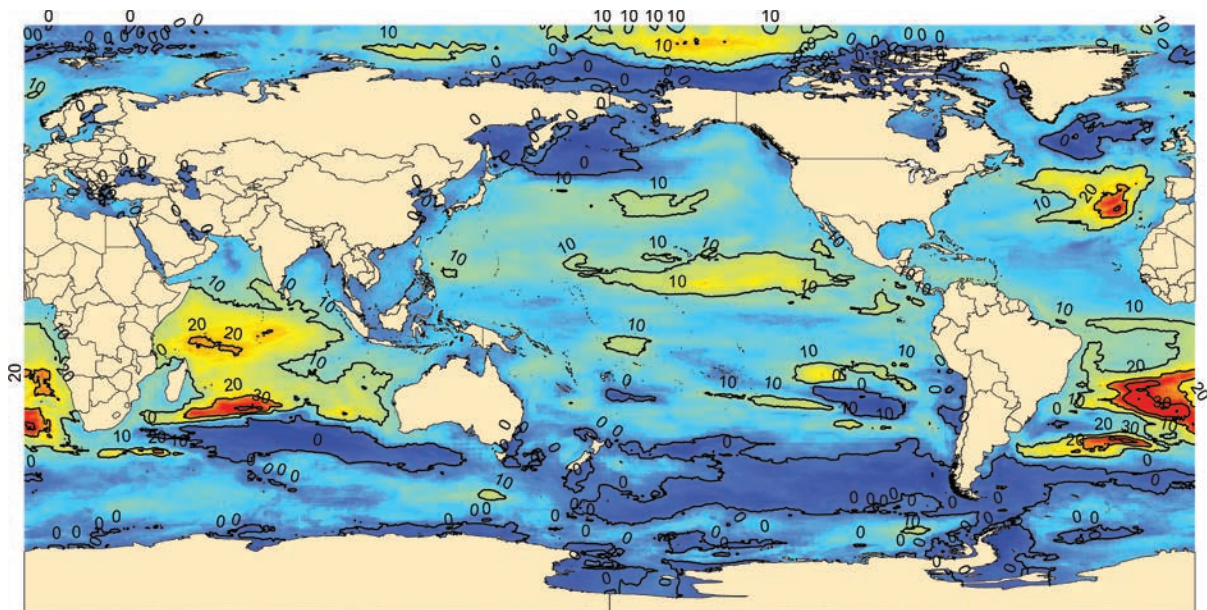


Figure 5.11. Color contour map shows the percentage change in dissolved iron between 2006 and 2050 under representative concentration pathway 8.5. Red areas show hot spots of the greatest increases, up to 30%. Data from CLIMsystems.

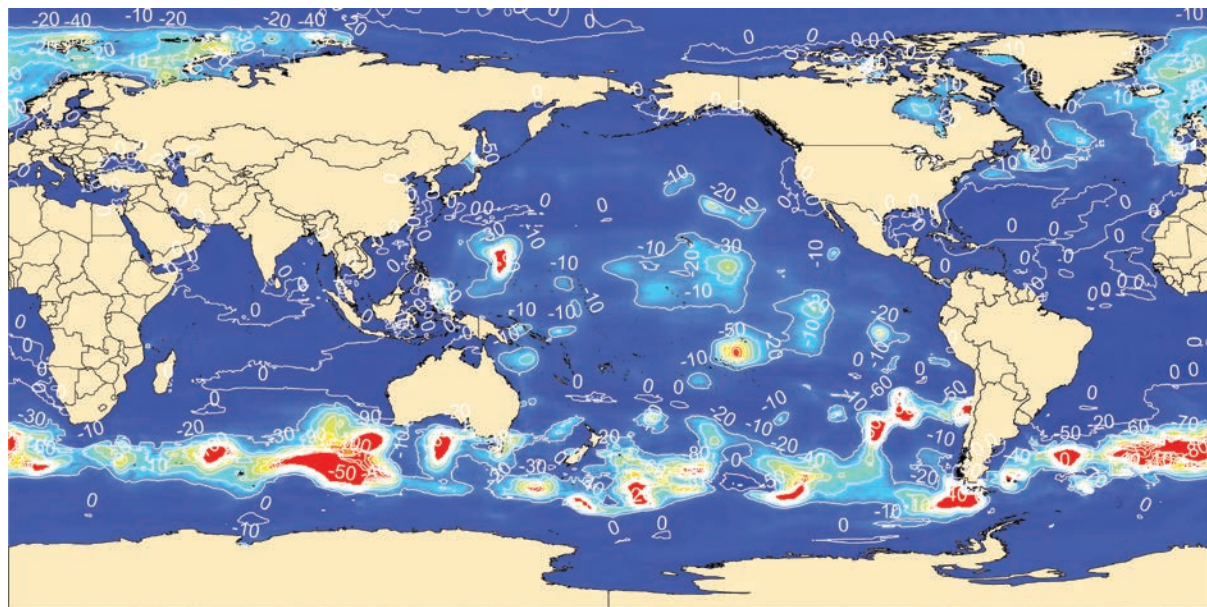


Figure 5.12. Color contour map shows the percentage change in dissolved silicate between 2006 and 2050 under representative concentration pathway 8.5. Red areas show hot spots of the greatest decreases, up to 50%. Data from CLIMsystems.

Discussion and Conclusion

The rapid ecological shifts that might occur in the world's oceans as a result of climate change present major challenges for managers and policy makers. Understanding and reducing risk exposure will become increasingly important as conditions change and the likelihood of major ecological shifts increases. These changes will decrease the relevance of current models and practices for managing ecological resources and fisheries stocks, leading the management of many ocean resources into "uncharted waters." Nonetheless, management strategies that reduce the impact of local stressors while maintaining ecological resilience will play an increasingly important role as the climate changes. Actions that reduce the flow of nutrients and sediments from coastal catchments, for example, as well as those that reduce activities such as the deforestation of mangroves and overfishing of key ecological species (e.g., herbivores), will become increasingly important as the impacts of climate change mount.

It is desirable to help decision-makers, especially in developing countries, better understand and assess the risks posed by climate change, and better design strategies to adapt their fishing sectors to climate change. The provision of scientifically robust climate change data in accessible formats (such as the results presented in this study) is a beginning. Training and capacity building is also critical, not only in the application of the data and tools but also in the interpretation of results. The importance of this stage is often overlooked, as it involves deeper understanding of the integration of data with management and policy and can often involve a myriad of stakeholders with different perspectives. The information derived from accessible data and tools can greatly enhance the latter process. It is especially desirable to have the capacity to integrate the analysis, for example, of dissolved iron, nitrogen, and phosphorus with SST or fish stock movements. Here, critical zones can be identified in which one or more variables, when combined, can show heightened risk or threatened resilience.

Another objective should be to develop global estimates of adaptation costs in, for example, the fisheries sector of countries to inform the international community's efforts; provide access to adequate, predictable, and sustainable support; and provide new and additional resources to help the most vulnerable developing countries meet adaptation costs. Results such as those presented in this study may be used to guide the prioritization of such adaptation options. Adaptation is here understood to mean any action taken to reduce the risk posed by the impact of climate change in a given sector of the economy (for example, fisheries). Adaptation cost is then the cost of taking such action. Yet the impact on ocean changes will extend well beyond fisheries and food security. Increasingly, tourism sectors represent important foreign-exchange earning engines for developing and developed economies. A sustained coastal ecosystem and its intrinsic values, and how they are threatened by loss of species diversity, can also be considered.

Ultimately, the ocean and terrestrial boundary offers countless local economic systems that have historically exploited this juxtaposition. These zones now extend to the farthest extent of a nation's Exclusive Economic Zone and beyond. Climate impacts are likely to affect both systems, but in different forms and at variable rates. However, these differences in no way diminish the need to see these zones holistically and visualize them as under threat from a changing climate. The transformation of voluminous climate data to knowledge products through the application of scientific methods and rapidly evolving spatial and analytical tools is more than important. It is critical.

Acknowledgments

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Supplemental Resources

Dawn J. Wright, ed.; 2016; *Ocean Solutions, Earth Solutions*, second edition; http://dx.doi.org/10.17128/9781589484603_5d

For the digital content that goes with this chapter, go to the book's online resources (esri.com/esripress-resources/ocean-solutions-2e). Some links and QR codes are also provided here.

SimCLIM for ArcGIS/Marine

- CLIMsystems/SimCLIM for ArcGIS/Marine, at <http://www.climsystems.com/simclimarcgis/marine/>



- SimCLIM ArcGIS/Marine add-in FAQ, at <http://www.climsystems.com/simclimarcgis/marine/faq/>



Downloadable Map Package

To download the digital content explained here, go to the book's online resources.

- SimCLIM for ArcGIS/Marine map package

For all the variables presented in this chapter, the map package contains both the baseline and climate-changed situation for 2050 under the assumption of the RCP8.5 emission pathway. This tool allows for further analysis of the climate change projection as well as usage of the variables in modeling dependent processes and variables. There is no restriction for the map's usage other than a proper reference to CLIMsystems. All layers have their relevant properties set and use the “cubic convolution (for continuous data)” resampling during display.

CHAPTER 6

A GIS Tool to Compute a Pollutant Exposure Index for the Southern California Bight

Rebecca A. Schaffner, Steven J. Steinberg, and Kenneth C. Schiff

Abstract

Southern California marine ecosystems face a variety of threats to their integrity and health as a result of their proximity to urbanized areas. These threats may be direct, through fishing and resource extraction, or indirect, through exposure to anthropogenic pollutants. Two primary sources of anthropogenic pollutants are treated wastewater, released by publicly owned treatment works through ocean outfalls, and freshwater runoff contained in urban river plumes. We developed a geospatial tool using ArcGIS software to calculate a pollutant exposure index for the Southern California Bight. The pollutant exposure index quantifies long-term exposure to potentially harmful pollutants emanating from these two sources. Recent studies on the dispersal of plumes have resulted in high-quality spatial datasets that predict plume occurrence frequencies as point grids around publicly owned treatment works and river mouths throughout the region. We multiplied the plume frequency values with data on average annual discharge rates, initial dilution factors, and concentration of chemicals in discharges to calculate the total exposure to pollutants at each location. Using this approach, we developed maps of the distribution of three important plume constituents: dissolved inorganic nitrogen in the form of nitrate and nitrite, total suspended solids, and copper. A series of Python scripts was created to facilitate geoprocessing of the exposure data and calculate the final pollutant exposure index raster, including (1) creating exposure rasters for each pollutant and source using inverse distance weighting, (2) summing publicly owned treatment works and river plume exposure rasters for each pollutant and normalizing each raster to the maximum exposure value, and (3) creating the pollutant exposure index by summing pollutant exposure rasters and normalizing again to provide values ranging from zero to one. The resulting georeferenced pollutant exposure index raster may be used with other spatial data to examine relative pollution risk for any area of interest within the mapped region. The pollutant exposure index will be incorporated into an ongoing study to examine relative risks posed to marine habitats by pollutants and pressure from fishing.

Introduction

The Southern California Bight (SCB) is an oceanographically defined region that extends from Point Conception in Santa Barbara County, California, to Cabo Colnett, Mexico, including the Channel Islands (figure 6.1). The SCB is a valuable natural resource that contributes to the regional economy and enhances the quality of life for those who work in, live in, or visit the area. Human uses of the coastline and ocean waters of the SCB include recreation, tourism, aesthetic enjoyment, sport and commercial fishing, coastal development, and industry. For example, ocean-dependent tourism contributed approximately \$41 billion to the economies of coastal communities surrounding the SCB and supported over 800,000 jobs in 2007 (National Ocean Economics Program 2008).

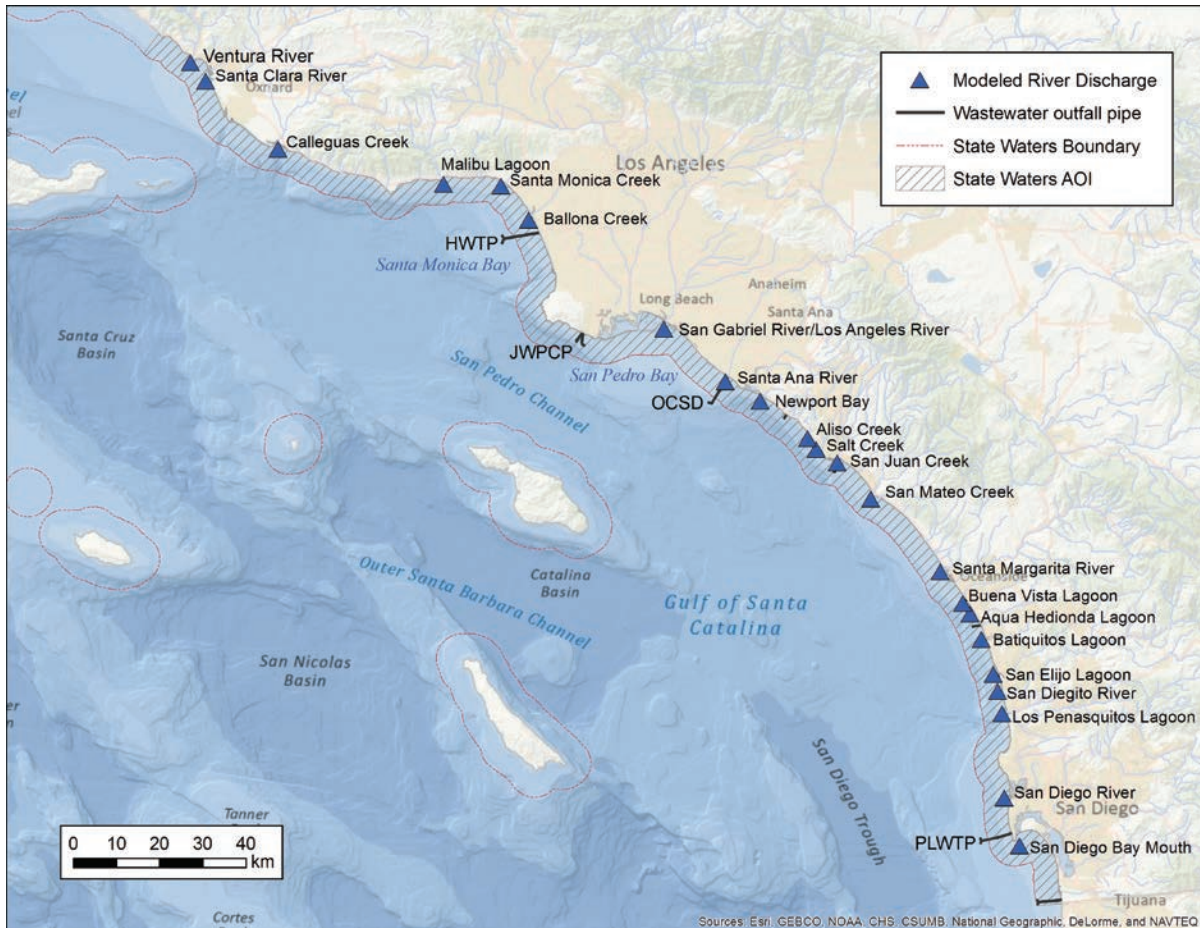


Figure 6.1. Map of the Southern California Bight shows the four major wastewater treatment plant outfalls: City of Los Angeles Hyperion Water Treatment Plant (HWTP), Los Angeles County Sanitation District Joint Water Pollution Control Plant (JWPCP), Orange County Sanitation District (OCSD), City of San Diego Point Loma Water Treatment Plant (PLWTP), and major river mouths that drain to the Southern California Bight. Also shown are the state offshore jurisdictional boundary and the boundary that encompasses the plumes analyzed in this study. Data sources: Esri, GEBCO, DeLorme, NaturalVue | Sources: Esri, GEBCO, NOAA, CHS, CSUMB, National Geographic, DeLorme, NAVTEQ.

The Southern California Bight Is a Valuable Resource

The SCB is a unique and highly diverse ecological resource (Schiff et al. 2000). For example, subtidal rocky reefs that support giant kelp (*Macrocystis pyrifera*) are among the most productive habitats in the world. The SCB is a primary stop along the Pacific Flyway, the major migration route for seabirds from North to South America. It also hosts a number of threatened and endangered species, including the blue (*Balaenoptera musculus*) and humpback (*Megaptera novaeangliae*) whales, California least tern (*Sterna antillarum browni*), and least Bell's vireo (*Vireo bellii pusillus*). Altogether, the SCB is home to over 5,000 species of invertebrates, 480 species of fish, and 195 species of marine birds (Dailey et al. 1993).

Human Influence in the Region

Throughout the 20th century, significant population growth propelled the coastal community along the SCB from under 200,000 in 1900 to over 17 million (US Census Bureau 2010), making the region the largest metropolitan center in the United States. As a result of rapid urbanization, marine resources in the SCB have been placed under extreme pressure, including loss of habitat and discharge of pollutants.

The SCB has a variety of pollutant sources, including publicly owned treatment works (POTWs), urban and agricultural runoff, industrial facilities, power-generating facilities, boating and shipping, dredged material disposal, and atmospheric deposition, among others (Schiff et al. 2000). Historically, the largest of these sources has been POTWs. With increased treatment, pretreatment, and reclamation, both total discharge rates and pollutant inputs from POTWs have decreased over the last four decades, greater than 90% for some individual pollutant types. However, surface runoff generated by storm events that washes off the region's highly developed watersheds delivers large pulses of potential pollutants that enter the ocean without any treatment. Flows and pollutant inputs from surface runoff have generally increased over this same time period as impervious surfaces (e.g., roads and rooftops) have hardened coastal watersheds. As a result, pollutant inputs from runoff now rival those of POTWs.

Of the 17 POTWs in the SCB, 4 comprise the vast majority of the discharge flow and pollutant inputs (Schiff et al. 2000). These four POTWs are among the largest in the United States and include the City of Los Angeles, County of Los Angeles, County of Orange, and City of San Diego (see figure 6.1), which cumulatively discharge over 800 million gallons of treated wastewater per day. These inputs remain relatively stable as flows are metered and treatment processes engineered to maintain a consistent effluent quality, but there has been a gradual downward trend in total discharge rates because of improvements in treatment and wastewater reclamation projects (Lyon and Sutula 2011).

The SCB has 23 major watersheds (see figure 6.1). Storm water discharges are highly variable, with infrequent but intense storms capable of increasing streamflow by three to four orders of magnitude in less than one hour (Schiff and Tiefenthaler 2011). Intensive storm water discharge after rainstorms can produce plumes that are easily distinguished from ambient marine waters by their high concentration of suspended matter that changes the color of the ocean surface (Mertes et al. 1998; Sathyendranath 2000; Mertes and Warrick 2001). The movement and persistence of plumes may be influenced by a variety of factors, such as wind and ocean circulation, coastline shape, and bathymetric variability, which may cause resuspension of sediments, as well as the volume, timing, and intensity of storm water discharge (Nezlin et al. 2005).

Study Objective

To date, no study has effectively used a geospatial approach to assess threats to water quality throughout the full extent of the SCB. Prior studies tended to focus on individual sources of pollution such as a single POTW outfall or individual watershed (Bay et al. 2003; Warrick et al. 2004; Ahn et al. 2005). Although these localized studies are valuable, they leave numerous gaps in both spatial and temporal coverage of the SCB, making it impossible to develop a comprehensive understanding of conditions and potential water quality threats. Furthermore, because each study used independent data and methods to assess water quality at a specific time and location, study results are not directly comparable. This variability results in a fragmented understanding of conditions in the SCB, making it difficult to understand how water quality conditions are changing over time as a result of management decisions or regulatory actions that are intended to protect and improve the water quality of the SCB.

To develop an accurate map of water quality conditions of the entire SCB requires data that is collected in a consistent manner and at an appropriate spatial scale. Such data has only recently become available through the efforts of coordinated regional monitoring programs such as those led by the Southern California Coastal Water Research Project (SCCWRP) (2014), datasets obtained from regional efforts such as the Southern California Coastal Ocean Observing System (SCCOOS), or satellite imagery data collected by the National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA).

Our objective was to develop geospatial tools in ArcGIS to model ocean exposure to land-based sources of pollution. Combining sources of newly acquired spatial data for the SCB with information on locations of pollution sources and inputs, we developed a series of Python scripts to calculate a composite pollutant exposure index (PEI) based on pollutant inputs from both POTWs and rivers. Developing tools such as the PEI provides several important benefits. The ArcGIS scripts provide a mechanism for assessing pollution impacts throughout the SCB in a consistent and repeatable manner. Second, these scripts provide a documented methodology that may be readily adapted by other researchers. This allows for adjustments that may be useful to incorporating data for additional pollutants or applying these methods in other locations.

For purposes of this study, we focused development of the PEI on three pollutants: dissolved inorganic nitrogen (DIN) in the form of nitrate and nitrite, total suspended solids (TSS), and toxic trace metals (copper). Selection of pollutants for development and testing of the tool was based on the following characteristics:

- The pollutant has known impacts on marine ecosystem health, either through direct toxicity or secondary effects by promoting growth of nuisance algal blooms.
- Datasets are available on the pollutant for both river and wastewater discharge sources.
- The pollutant is discharged frequently and in large enough quantities that it is likely to have significant and ongoing effects on marine ecosystems.
- The pollutant represents a range of sources such as urban, agricultural, or industrial activities.

Nitrate is a critical plant nutrient necessary for the growth of phytoplankton, sea grasses, kelp, and other macroalgae. However, in large concentrations, nitrate can promote the growth of harmful algal species and cause phytoplankton blooms (Anderson et al. 2008). Recent studies have found that treated effluent may have nitrate concentrations equivalent to natural sources such as upwelled seawater (Howard et al. 2014).

TSS can negatively impact nearshore subtidal communities, reefs, and kelp beds through reduction of the availability of light and, in large quantities, by smothering benthic organisms. Episodic riverine TSS inputs can be quite large in some regions such as the Santa Clara River (up to 5.5×10^7 kg/yr). Additionally, other toxic chemicals adsorb onto the surface of particulate matter, creating a large-scale transport mechanism between the water column and benthic substrates (Hart 1982).

Copper is a trace metal that can cause both acute (lethal) and chronic (impaired growth, reproduction) effects in marine organisms. Copper is a by-product of some industrial activities and a common contaminant found in storm water. Its ubiquity in storm water stems from its use in vehicle brake pads, pesticides, and building materials and from atmospheric deposition (Davis et al. 2001). Copper toxicity to marine plants and invertebrates is so prevalent that it is often used as a biocide in paints used to coat the bottoms of boats and docks. Copper does not transform easily and can settle into ocean sediments, exerting long-term effects (Long et al. 1995).

Methods

We used a regional-scale risk-based approach to creating the PEI. The risk was estimated as a function of pollutant concentration, magnitude, and duration of exposure. Therefore, the primary factors for the index were pollutant loading and pollutant plume frequency. Pollutant loading was estimated for the SCB's two largest sources, POTWs and rivers. Spatial distribution of exposure duration was acquired from multiple sources that use advances in plume detection technology. Table 6.1 lists the sources of data used for the water quality index (WQI). Many of the geoprocessing tasks were automated using the ArcGIS ModelBuilder application and Python scripts.

Table 6.1. Sources of Spatial Data and Pollutant Loading Data for POTWs and River Plumes

Pollutant Source	Loading Data	Frequency Data	References
Wastewater treatment plants	Discharge monitoring reports; Bight 2008 water quality study	CDOM plume detection method	Lyon and Sutula 2011 Howard et al. 2014 Nezlin et al. in prep.
River plumes	Riverine loading model	HFR-based surface circulation models	Sengupta et al. 2013 Rogowski et al. 2014

Riverine Pollutant Loading

A rational model was developed that uses precipitation data, watershed size, and land cover to predict daily loads of chemicals from watersheds (Ackerman and Schiff 2003; Sengupta et al. 2013). For 23 rivers, we calculated average annual loads of DIN, TSS, and copper based on 11 years of data (2000–2010). Watershed sizes for these rivers range from 25 to 4,486 sq km and comprise a wide range of predominant land uses, including urbanized (i.e., residential, commercial, and industrial areas), agricultural lands, and open space (i.e., largely undisturbed areas of wetlands, forest, or scrub/shrub vegetation [Sengupta et al. 2013]). The model ignores base flows that result from inland sewage treatment discharges and general dry-weather runoff. For the purposes of this study, we assumed that base river flows are a minor source of pollutants whose effects do not radiate far from river mouths.

Each river mouth was treated as a single point source. Pollutant loads were multiplied by a dilution factor of 1:100 to account for estuarine mixing processes and the loss of the pollutant from the plume as it entered the ocean. This factor was selected based on studies that show that during storm events, only about 1% of the TSS originating from riverine inputs is found in the surface plume offshore of river mouths. The majority of sediment settles in the estuarine mixing zone and within 1 km of the river mouth (Mertes and Warrick 2001; Warrick et al. 2004).

Riverine Plume Mapping

Southern California river plumes have been mapped using several different methods, primarily satellite imagery in combination with in situ sampling of plume tracers (Otero and Siegel 2004; Nezlin et al. 2005; Warrick et al. 2007; Nezlin et al. 2008; Reifel et al. 2009). These methods provide empirical data on plume locations and extents but have several limitations. Generally, they focus on limited areas and individual storm events. Cloud cover can interfere with accurate imaging, preventing visualization of the plume during inclement weather when plumes are forming and dispersing. Remotely sensed plume indicators tend to correlate with the presence of suspended solids in surface waters but may not always agree with the concentrations of other dissolved pollutants. One alternative method of mapping plume probability is the use of high-frequency radar (HFR) to model the dispersion of surface water tracers seeded into regions of river discharge. HFR-derived surface currents over a given temporal period are input into a random walk model (Kim et al. 2009; Rogowski et al. 2014). Rogowski et al. (2014) used HFR surface current data to model the probability of plume exposure for 20 river discharges in Southern California, based on two years of hourly surface current data. In the Rogowski et al. model, 50 water tracers were released hourly at each source location (1 km offshore) and independently tracked for three days. A probability density function was used to compute the cumulative sum of water tracers that advected into predefined model grids that surround each river mouth source location. These grids vary in point density and may overlap (figure 6.2).

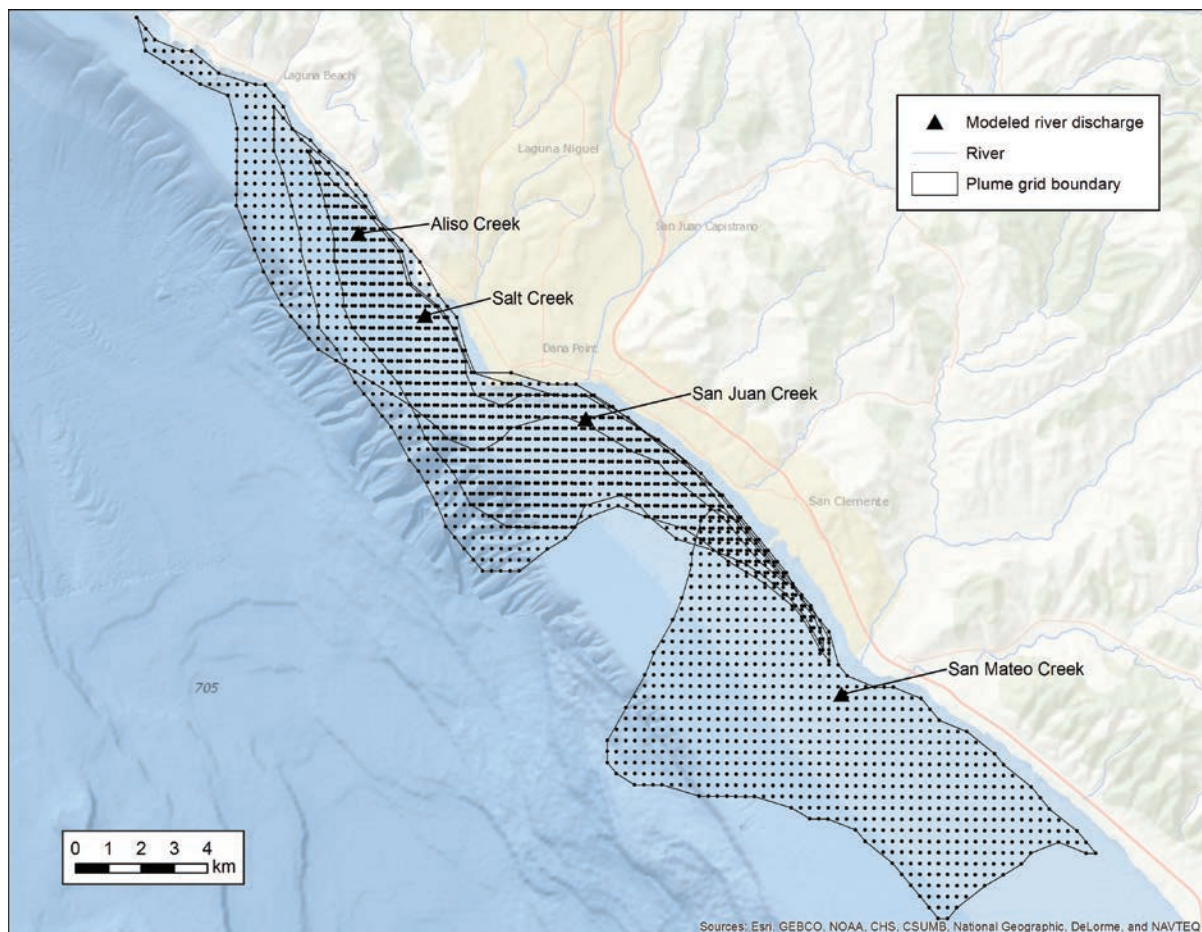


Figure 6.2. Four overlapping river plume grids in Orange County, California. Data from the authors, Esri, GEBCO, NOAA, CHS, CSUMB, National Geographic, DeLorme, NAVTEQ.

Final river plume probability exposure maps used many realizations (with the number varying among the grids) of hourly water tracer trajectory estimates to determine statistical convergence over various time periods. We converted the model output for each river plume into a point feature class that represents the centroid of each grid cell, with a river plume exposure probability (RPE) attribute field. The RPE was calculated for each cell based on the maximum number of particles observed at a single point within the grids. Probabilities ranged from 0 to 1; and to reduce noise and eliminate probable nonplume regions of the grids, only cells with a value of ≥ 0.01 were included in the spatial analysis. This value was also used to identify the maximum extent of each plume and create individual plume boundary polygons to clip interpolated raster layers.

To calculate the exposure for each cell, the riverine loading value for each constituent was multiplied by the dilution factor and RPE in equation (6.1):

$$\text{Exposure} = \text{Load} \times \text{Dilution} \times \text{Frequency.} \quad (6.1)$$

We developed Python scripts to automate most of the subsequent geoprocessing tasks (figure 6.3). For each river plume and parameter, exposure values were interpolated across each grid using inverse distance weighting (IDW), an exact interpolator which assumes that the influence of a known point on an unknown location varies inversely with the distance between the points. It is a simple interpolator that ignores all factors other than the distance between points. We selected IDW because sufficient datasets are not available to describe the complex variables that affect plume distributions at the scale of the study region and time period necessary for parameterizing more sophisticated interpolators such as kriging. The 20 individual river plume exposure grids were interpolated to rasters using a power of 2, a resolution of 250 sq m, and a maximum search radius of 10 km. The interpolated plumes were clipped by the corresponding plume boundary polygon, NoData values were converted to 0, and the spatial extent of the raster was set to the maximum extent of all plumes (river and POTW) to simplify integration of the various layers. The 23 plume rasters were then summed to create a single layer that represents the bightwide exposure for each chemical, and a plume boundary polygon that encompassed all 23 grids was created. Finally, the Zonal Statistics tool in ArcMap was used to calculate spatial statistics for the resulting pollutant exposure raster layers, including mean, median, and maximum values, using the bightwide plume boundary polygon as the zone. This polygon exactly encompasses all points in the plume grids and was created using the Aggregate Points tool in the Generalization section of the Cartography toolbox in ArcMap (see figure 6.3).

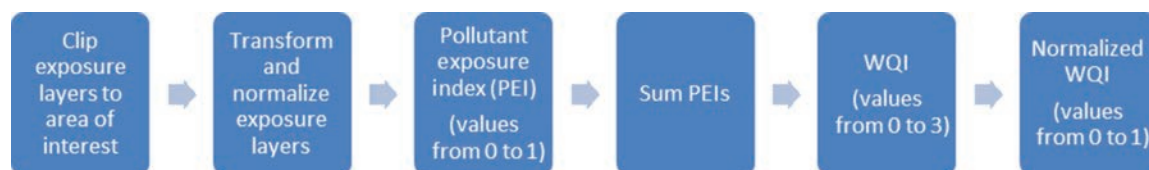


Figure 6.3. Workflow shows the geoprocessing steps used in the interpolation of pollutant exposure index rasters and calculation of the pollutant exposure index raster.

Sewage Discharge Pollutant Loading

Monthly discharge flow rates and concentrations of copper and TSS from four major Southern California sewage treatment plants were obtained from Discharge Monitoring Reports that each agency is required to submit to the US Environmental Protection Agency (EPA) (Lyon and Sutula 2011). DIN concentrations in effluent were acquired from a recent study that directly measures

nutrients in treated wastewater discharge (Howard et al. 2014). The four POTWs used for this analysis—City of Los Angeles Hyperion Water Treatment Plant (HWTP), Los Angeles County Sanitation District Joint Water Pollution Control Plant (JWPCP), Orange County Sanitation District (OCSd), and the City of San Diego Point Loma Water Treatment Plant (PLWTP)—are shown in figure 6.1. The average annual load of each pollutant from each plant was calculated for the period 2003–9. An instantaneous dilution factor was applied to the loading value to account for immediate dilution of discharged effluent in seawater before dispersal occurs. This dilution factor is calculated individually for each outfall as part of the permitting process, based on empirical data that compares concentrations in the undiluted effluent with concentrations in the seawater immediately adjacent to the outfall (EPA 1985).

Sewage Discharge Plume Mapping

Wastewater outfall plumes are typically modeled by measuring plume tracers such as salinity, ammonia, and bacteria at stations that surround the outfall. These approaches can be time consuming and costly, so alternative methods of detecting plumes are being assessed. Nezlín et al. (in preparation) used measurements of colored dissolved organic matter (CDOM) to rapidly measure and track plumes emanating from subsurface discharge outlets at the four large sewage treatment plants. Each POTW agency regularly samples water quality at a grid of stations that surround their outfall pipes (figure 6.4). CDOM datasets were collected at each station on a quarterly basis from 2004 to 2010. For each station, the percentage of sampling events when a plume was observed (at any depth between the outlet and below the mixed layer) was calculated as wastewater plume exposure (WPE). The four individual sampling grids were combined into a single point feature class, and each point was attributed with its associated WPE value.

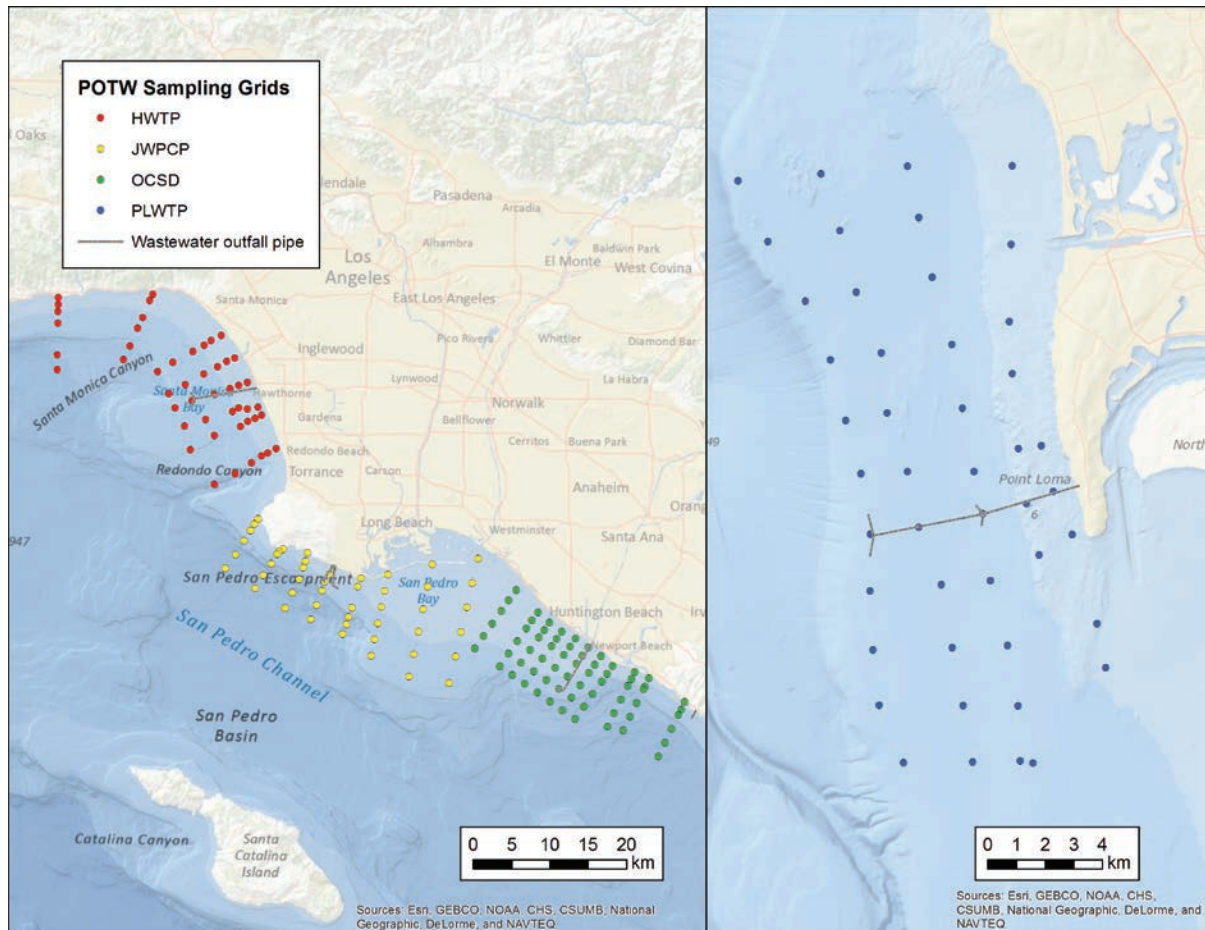


Figure 6.4. Grids of water quality stations sampled quarterly by each publicly owned treatment works (POTW) agency. The distance between stations varies. The stations are the City of Los Angeles Hyperion Water Treatment Plant (HWTP), Los Angeles County Sanitation District Joint Water Pollution Control Plant (JWPCP), Orange County Sanitation District (OCSD), and City of San Diego Point Loma Water Treatment Plant (PLWTP). Data from Esri, GEBCO, NOAA, CHS, CSUMB, National Geographic, DeLorme, NAVTEQ.

We assumed that plume probability at a given grid point is directly equivalent to the dilution of the treated effluent as it is advected away from the source and that dilution of each chemical within the outfall plume also varies in proportion. Pollutant exposure at each point was calculated using equation (6.1). The exposure values were interpolated across the grid using IDW with a power of 2, a resolution of 250 sq m, and a maximum search radius of 10 km. A linear shoreline layer was used as a barrier to prevent interpolation of plumes over land areas.

Merging the Pollutant Exposure Layers and Creating the PEI

The geoprocessing steps described in the previous section resulted in six rasters, which represent the distribution of each of the three pollutants from both rivers and POTWs within the SCB. For each pollutant, we summed the river plume and wastewater discharge plume rasters to create a single total exposure raster. Each parameter was then normalized to the maximum value before integration into the single index. This was a two-step process. First, to reduce skewness for each individual parameter, we calculated the cube root of each raster cell. The cube-root value of each raster cell was divided by the maximum value found in the grid, resulting in a PEI layer with values that range from 0 to 1

for each chemical. These three normalized PEIs were summed to create a new raster with potential values that range from 0 to 3. Finally, the cells in this raster were divided by the maximum value in the raster to create the normalized PEI raster, with continuous values that range from 0 to 1 (see figure 6.3).

Sensitivity Analysis

We conducted a sensitivity analysis to assess the variability in riverine pollutant loadings and the exposure between wet and dry years. Representative wet and dry years in our 10-year dataset were based on long-term (63 years) rainfall records from three Southern California rain gauge stations (Los Angeles International Airport, Santa Ana Fire Station, and San Diego Lindbergh Field) downloaded from the NOAA National Climatic Data Center (2014). Total rainfall from 2007 (8.2 cm) was less than the 10th percentile of the long-term average. Total rainfall from 2010 (51.3 cm) was greater than the 90th percentile of the long-term average.

For 2007 and 2010, we calculated the total annual loads of each chemical and compared the resulting range of values to the 10-year average annual loading value for each parameter and watershed. Exposure layers were created for both 2007 and 2010 using equation (6.1) described previously, and the total spatial variation in loading was mapped and analyzed. To examine spatial bias, the 20 river plumes assessed were grouped into four regions: Ventura County, Santa Monica Bay (SMB), Orange County, and San Diego County.

Results

Spatial Extent of Plumes

By design, outfalls of wastewater treatment plants are located greater than 8 km offshore and at depths between 60 and 100 m to inhibit effluent from recirculating back into surface and nearshore waters. By contrast, plumes that emerge from river mouths are immediately subject to multiple nearshore processes, including estuarine mixing, entrainment in the surf zone, and exposure to surface currents. The resulting differences in the fates of riverine and wastewater plumes are shown in figure 6.5. Wastewater plumes are observed most frequently in the immediate vicinity of the outfalls and are carried by prevailing subsurface currents either upcoast or downcoast of the pipe. They rarely reach shallow water, generally occurring within 2 km of shore less than 20% of the time. By contrast, riverine plumes tend to hug the shoreline, with the predominant direction depending on prevailing surface currents. Rapid settling and mixing processes prevent freshwater inputs from extending too far into the ocean, except under extraordinary climatic conditions and flood events. As a result, the portion of river plumes with the greatest concentration of pollutants occurs within 2 km of shore.

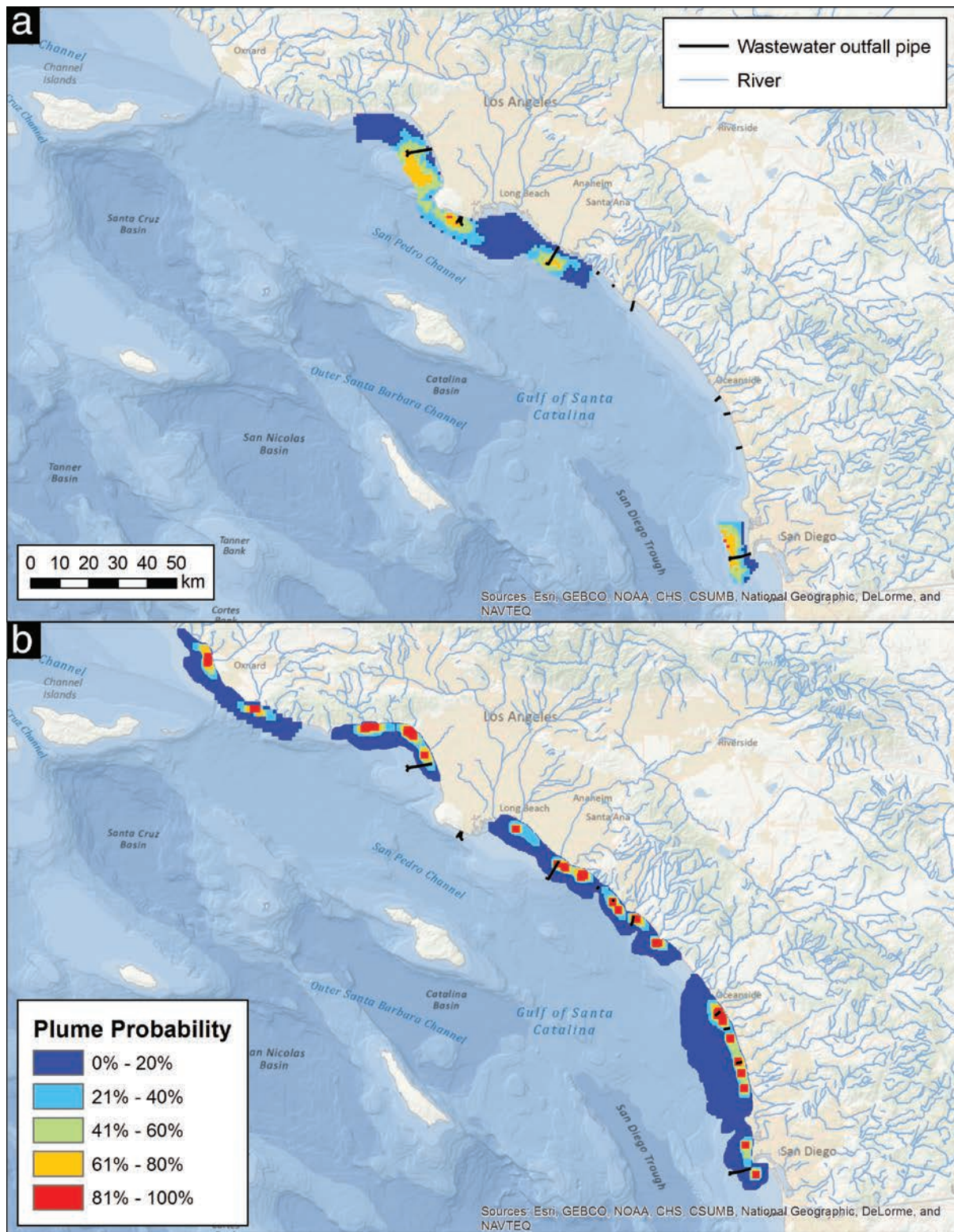


Figure 6.5. Maps show (a) wastewater treatment plant plume probability and (b) river plume probability.

Data from the authors, Esri, GEBCO, NOAA, CHS, CSUMB, National Geographic, DeLorme, NAVTEQ.

Pollutant Loading and Exposure

The relative loadings of the three pollutants vary between sources, and their spatial distributions within the area affected by plumes vary correspondingly. We calculated exposure statistics for individual and combined pollutants across the entire region, including the annual median, mean, and maximum exposure values (table 6.2). For all pollutants, the median exposure is lower than the mean, and both values are extremely low compared with the maximum exposure value. This skewness reflects the fact that even within coastal waters impacted by plumes, exposures are generally low over much of the affected area. However, localized areas may be at risk where maxima occur.

Table 6.2. Spatial Statistics for Individual Pollutants by Source

Source Parameter	Plume Area (km²)	Average Annual Load (kg/yr)	Exposure (kg/yr)		
			Median	Mean	Max
POTWs					
Copper	1178.9	2.62 × 10 ⁴	6.5	13.7	81.2
DIN		2.99 × 10 ⁶	261.8	2813.9	25,502.8
TSS		3.39 × 10 ⁷	11,183	171,670	89,800
Rivers					
Copper	1594.3	1.37 × 10 ⁴	0.2	0.7	25.4
DIN		9.47 × 10 ⁵	15.2	49.4	2070
TSS		1.72 × 10 ⁸	2832	9478	505,746
Combined					
Copper	2433.1	4.0 × 10 ⁴	1.2	7.1	81.2
DIN		1.25 × 10 ⁶	37.3	1396.9	25,502.8
TSS		2.06 × 10 ⁸	6163	14,527	505,746

Copper

Large POTWs contribute nearly twice as much copper to the SCB as the rivers considered in this study (see table 6.2). Maximum exposures occur near the HWTP outfall, in Santa Monica Bay. Riverine exposure to copper is highest in the vicinity of the Los Angeles and San Gabriel River mouths, in San Pedro Bay. The Santa Clara River also contributes high loads of copper to the coast of Ventura County.

Dissolved Inorganic Nitrogen

POTWs also contribute three times as much DIN as rivers (see table 6.2). This figure agrees with recent studies that show that wastewater discharge represents the dominant anthropogenic source of nitrogen to the SCB (Howard et al. 2014). As with copper, the highest exposures from wastewater sources are found near the Hyperion outfall. The small but highly urbanized Ballona Creek watershed also contributes relatively high amounts of DIN to Santa Monica Bay (figure 6.6a–b). As with copper, the Los Angeles and Santa Clara Rivers contribute the most riverine DIN overall. The Los Angeles River is predicted to load an average of 219,524 kg/yr, and the Santa Clara River contributes 121,159 kg/yr.

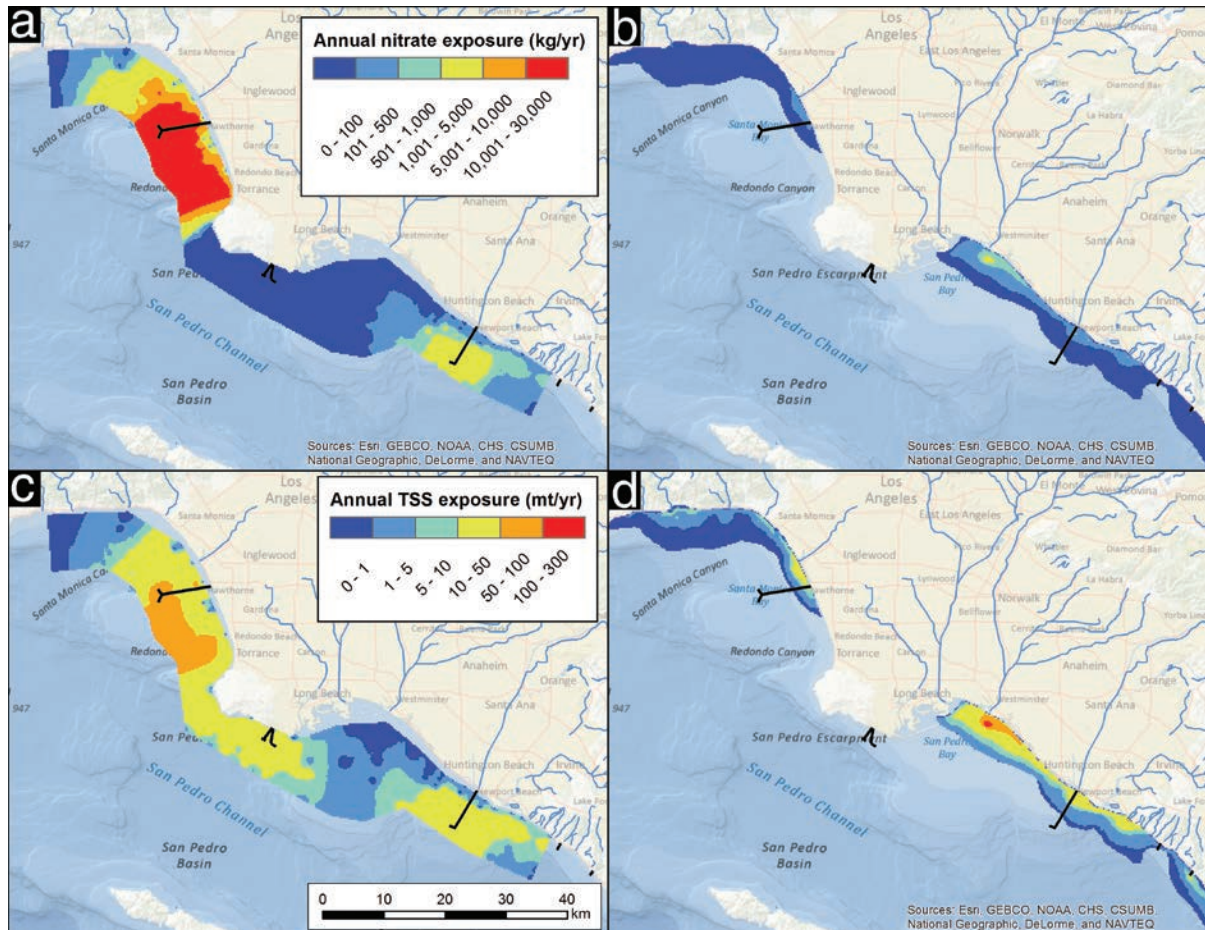


Figure 6.6. Comparison of pollutants by source in Santa Monica Bay/San Pedro Bay: (a) dissolved inorganic nitrogen exposure from publicly owned treatment works, (b) dissolved inorganic nitrogen exposure from rivers, (c) total suspended solids (TSS) exposure from publicly owned treatment works, and (d) total suspended solids exposure from rivers. Data from Esri, GEBCO, NOAA, CHS, CSUMB, National Geographic, DeLorme, NAVTEQ.

Total Suspended Solids

In contrast to copper and DIN, sediment inputs are dominated by riverine loading, which contributes five times the TSS of POTWs (see table 6.2). Three of the four POTWs employ secondary treatment (activated sludge or biological reactors), which reduces the amount of suspended solids discharged offshore. There are no such controls on the sediments that enter rivers via runoff, especially from watersheds in which elevation gradients and land use contribute to high sediment levels. Thus, although offshore exposures from POTW discharges are highest in Santa Monica Bay (figure 6.6c) and offshore of Point Loma, San Diego; they are low in comparison to riverine TSS exposures, particularly from the northernmost watersheds in this study (Ventura River, Santa Clara River, and Calleguas Creek). These watersheds have the highest elevations, most erosion-prone soil types, and greatest rainfall quantities, as well as large areas of agricultural land. As a result, the highest TSS loadings and exposures are found in the nearshore waters of Ventura County. Urbanized areas such as the watersheds that empty into San Pedro Bay also contribute high TSS loads (figure 6.6d).

Pollutant Exposure Index

The PEI developed through this process is designed to be adaptable for use in comparing different polygonal areas of interest within the larger SCB. Figure 6.7 maps the combined PEI score across the bight. For the purpose of this study, the area of interest (AOI) is defined as California state waters inshore of the 3 nm State Seaward boundary and that extend from the Mexico border to the northernmost extent of the mapped plumes (hatched area, figure 6.7). Table 6.3 summarizes the percentage area within the AOI found within each range of the normalized PEIs for individual parameters, and the normalized PEI. Over 45% of the total AOI had a PEI score of $>0-0.3$. Another 24.2% is not covered by any mapped plume. The river plume model includes all major rivers but omits some smaller coastal watersheds and catchments. However, most of these omissions are relatively undeveloped and unlikely to be major sources of pollutants.

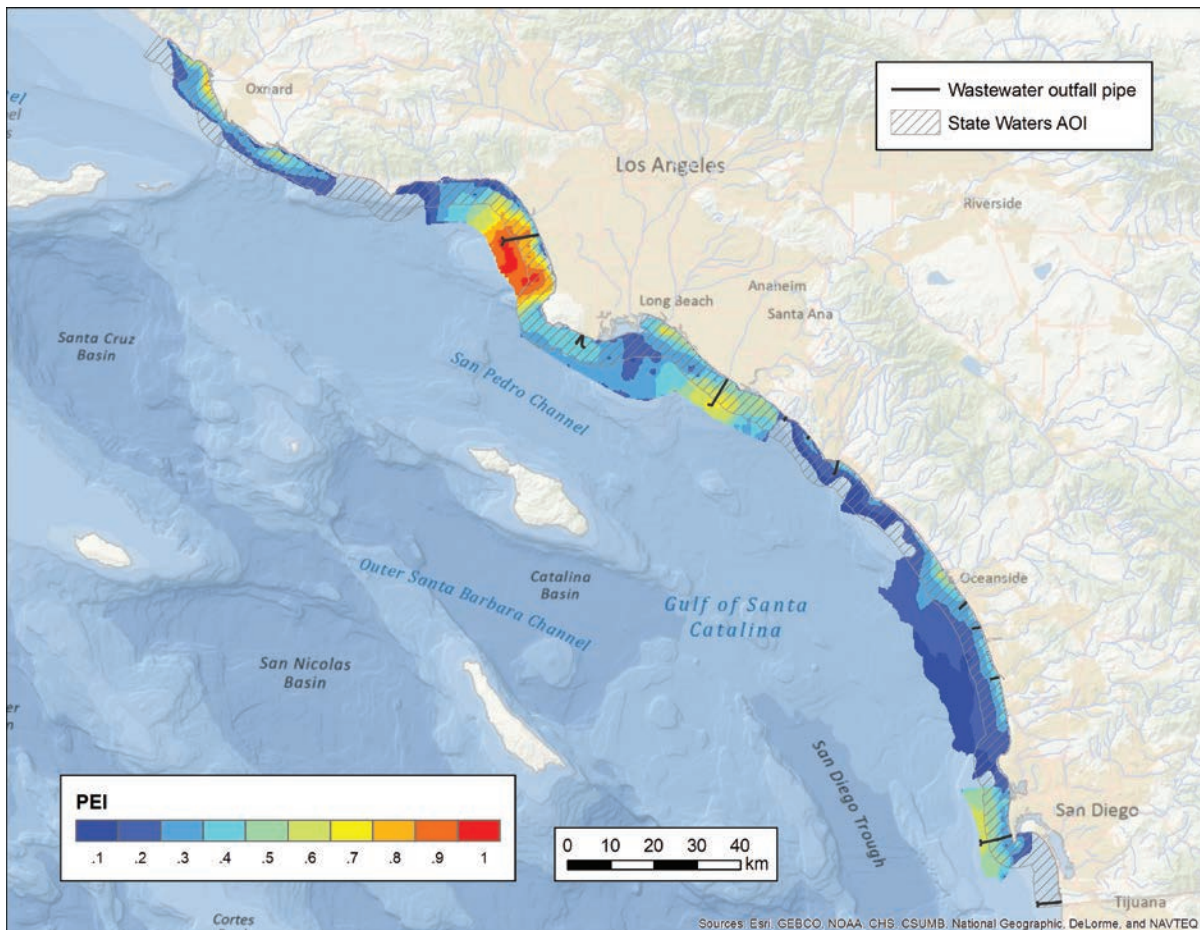


Figure 6.7. Map of pollutant exposure index (PEI) based on combined sources, including state waters areas of interest (AOIs). Data from Esri, GEBCO, NOAA, CHS, CSUMB, National Geographic, DeLorme, NAVTEQ.

Table 6.3. Percentage Area of California State Waters (inside the 3 nm Limit) within Each Class of the Pollutant Exposure Index for Individual Parameters and the Combined Pollutant Exposure Index (total area = 1986.7 km²)

	Percentage of SCB Area for Each Pollutant Exposure Index Class										
	No Plume	>0 to 0.1	>0.1 to 0.2	>0.2 to 0.3	>0.3 to 0.4	>0.4 to 0.5	>0.5 to 0.6	>0.6 to 0.7	>0.7 to 0.8	>0.8 to 0.9	>0.9 to 1.0
Copper	24.2	8.2	20.6	15.9	10	8.2	4.6	3.7	3	1.4	0.2
DIN	24.2	28.9	25.5	10.2	3.4	1.2	1.1	1.3	2.4	1.5	0.3
TSS	24.2	4.6	20.2	22.1	19.2	7.3	1.5	0.4	0.2	0.1	0.1
All	24.2	6.5	19.5	19.3	13.4	7.8	3.2	1.8	2.6	1.4	0.3

Sensitivity Analysis

The interannual variability in precipitation is reflected in the total riverine pollutant loading and the spatial extent of plumes (figure 6.8). In dry weather, plumes are ephemeral and restricted to within a few kilometers of river mouths. With increasing precipitation, plumes extend both alongshore and offshore, and plumes from adjacent river mouths may merge. Table 6.4 and figure 6.9 compare the regional mean and maximum exposure values between dry, average, and wet years. In all regions, dry years produce about 20% of the total loads of wet years, whereas average years produce about 45% of the loads of wet years. Such interannual variability can play a large role in the integrity of coastal ecosystems. For example, several dry years in a row may allow the establishment of habitats and communities that may be severely impacted by heavy flows and pollutant inputs in a subsequent wet year.

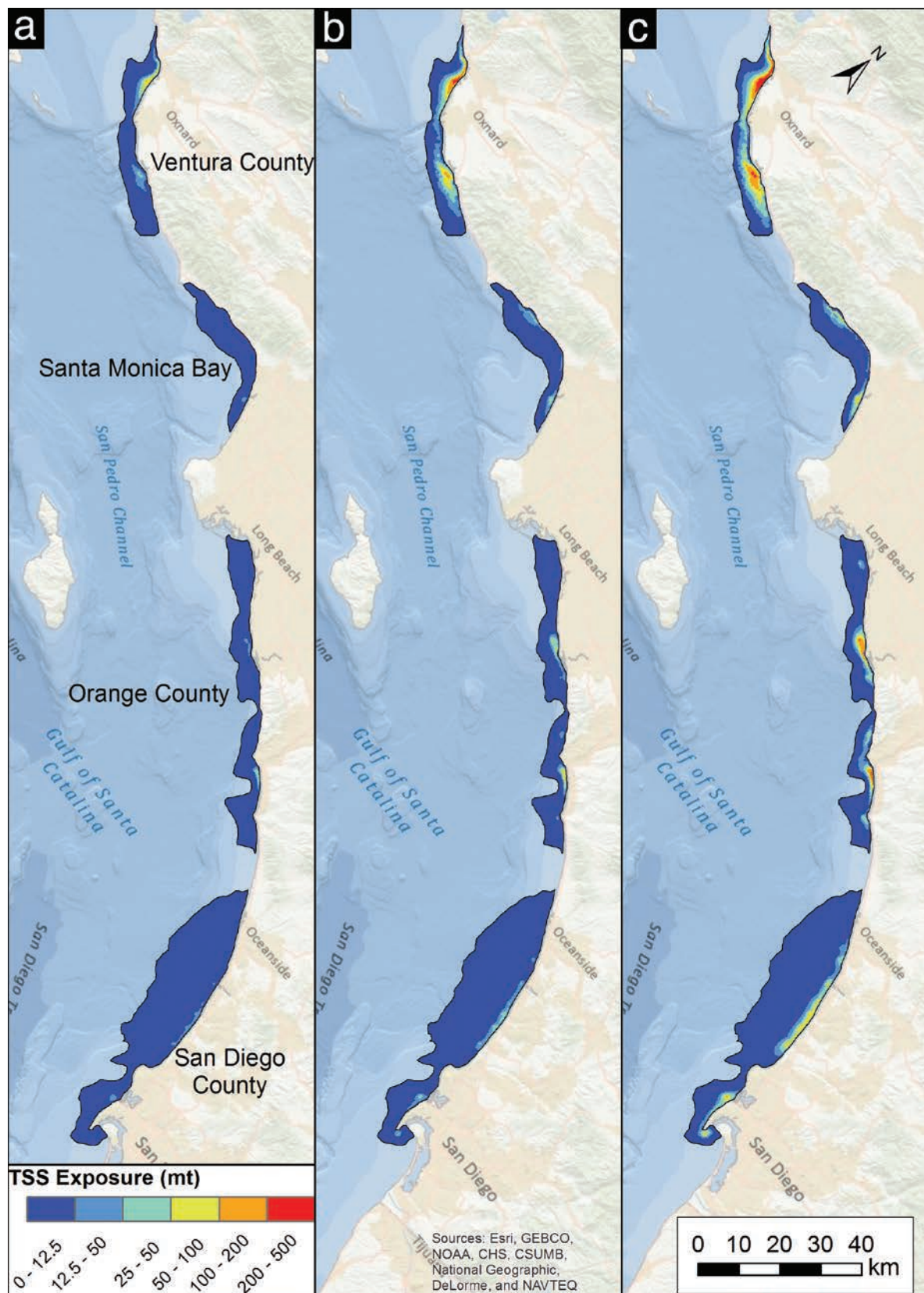


Figure 6.8. Maps compare total suspended solids (TSS) exposures for (a) dry, (b) average, and (c) wet years. The mapped plumes are grouped into four regions. Data from the authors, Esri, GEBCO, NOAA, CHS, CSUMB, National Geographic, DeLorme, NAVTEQ.

Table 6.4. Sensitivity Analysis: Summary Statistics by Pollutant and Region

	Mean Exposure (kg/yr)			Maximum Exposure (kg/yr)		
	Dry	Average	Wet	Dry	Average	Wet
Copper						
Ventura	0.11	0.32	0.61	1.66	4.13	7.52
SMB	0.04	0.12	0.24	1.03	2.39	5.49
Orange	0.03	0.07	0.18	0.78	1.73	3.93
San Diego	0.16	0.29	0.80	2.84	4.61	14.19
Nitrate						
Ventura	7.2	21.5	40.6	109.7	273.7	498.4
SMB	3.1	9.0	18.2	82.2	190.1	439.9
Orange	1.8	4.6	12.3	52.7	116.8	265.1
San Diego	10.6	18.4	50.8	183.4	297.9	871.3
TSS						
Ventura	7070	21,013	39,643	107,267	267,515	487,234
SMB	1201	4527	7743	18,312	44,679	94,354
Orange	1501	3893	10,739	42,135	95,163	226,030
San Diego	1249	2178	6016	24,564	38,016	102,712

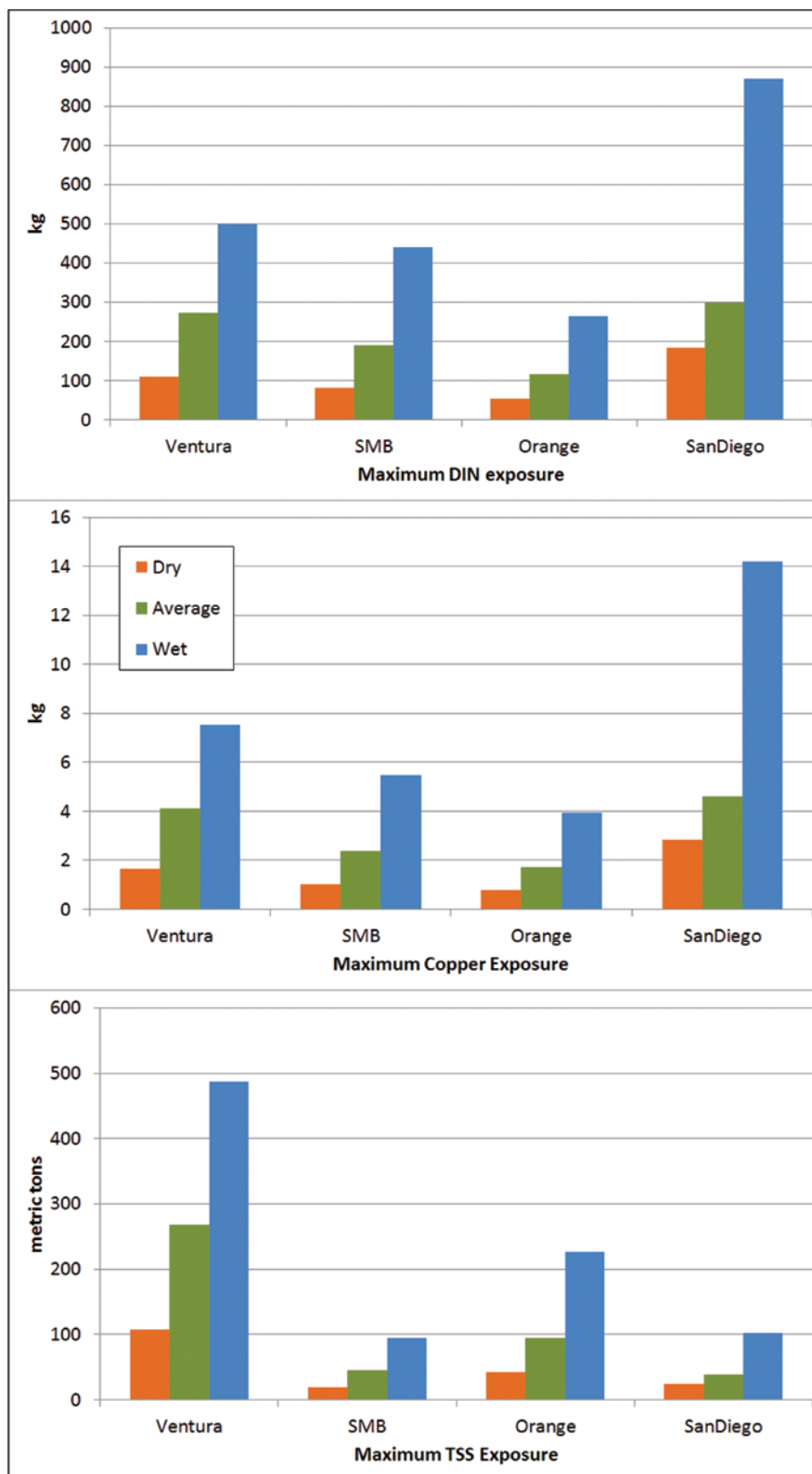


Figure 6.9. Comparison of pollutant exposure (dissolved inorganic nitrogen, copper, and total suspended solids) by region during dry, average, and wet years.

Discussion

As development and population growth continue within watersheds that are adjacent to the SCB, loads of potentially harmful and toxic chemicals may present a risk to the many valuable resources from both river runoff and treated wastewater. Little is known about the spatial extent of the relative and combined effects of these pollutant sources in different areas of the SCB. With new methods of plume detection, we can now more effectively map and analyze these datasets. Regional-scale spatial analysis of freshwater plumes and pollutant exposures in the marine environment is a relatively new and growing field. To date, few studies have been done to examine regional extents and effects of plumes (Mertes and Warrick 2001; McLaughlin et al. 2003; Álvarez-Romero et al. 2013). As consistent and comparable datasets become more readily available through advances in both in situ sampling instruments and remote-sensing systems, in conjunction with increasing data-processing power, the opportunity to conduct regional spatial analysis and modeling of these datasets is feasible. Satellite imagery allows us to distinguish plumes from ambient water over large areas and longer time scales. Technologies such as HFR aid in the localized prediction of currents and particle movement through surface water. New sensor applications, such as CDOM, enable researchers to capture subsurface water quality information more quickly, consistently, and economically than they could using traditional sampling techniques.

Benefits of Using GIS to Create a Regional PEI

Our development of geoprocessing tools to spatially integrate these datasets with information on pollutant loads to create a regional PEI provides an important next step in mapping and understanding potential threats to water quality in the SCB. This index enables a consistent approach to quantifying the spatial extent of exposure to these pollutants and identifying critical coastal habitats that may be affected. These tools encapsulate numerous geoprocessing steps into a documented, transferable, and modifiable package. Most of the repetitive steps of this analysis, including the interpolation of individual plume frequency grids, summing of rasters, and generation of spatial statistics, were quickly accomplished by creating models in ModelBuilder or developing Python scripts. These tools can be customized to accept different input variables rather than being hard-coded with set parameters, increasing their flexibility. The separate scripts may then be packaged into an ArcGIS toolbox, which is easily shared with others who wish to perform similar analyses.

GIS also allowed for spatial integration of datasets that were acquired through different methods and sources. Datasets from multiple studies and sources can be integrated as long as they have sufficient resolution and similar spatial referencing. In this study, we combined plume frequency data from the two primary sources, POTWs and rivers. The POTW plumes were empirically mapped using field sampling techniques (CDOM detectors), while river plume locations were modeled based on interpretations of surface current data. Despite these different approaches, both methods resulted in a simple grid of points attributed with a predicted plume frequency, enabling us to apply similar calculations and interpolation methods to both datasets.

Another advantage of using GIS to model plume exposures is that variables can be easily modified to reflect different environmental conditions and predict different outcomes. For example, the Southern California climate is characterized by high interannual variability in precipitation. This variability has significant effects on the annual loading of pollutants by river plumes. In some years (such as those when El Niño conditions prevail), this variability can result in massive inputs of sediment, nutrients, and metals; while in other years, the inputs barely rise above baseline. Fortunately, the loading model we used explicitly incorporates precipitation as a variable in predicting loads and provides data on a daily basis, enabling us to subset the data into years that reflect this natural climatic variability. These

subsets provide representative end-members for our sensitivity analysis. Other variables that can be modified include the dilution factors used to represent initial loss of pollutants from the plume. Flexibility to adjust these tools to match regional requirements provides a distinct advantage, reducing the need for expensive, long-term empirical field-sampling efforts to capture natural variability.

These GIS-based index development tools have some limitations. Because it is two-dimensional, the model does not incorporate the dispersal of pollutants with depth, or reflect complex oceanographic mixing processes, and is therefore only applicable to nearshore shallow water. The strength of its predictive capabilities lies in the methods used to integrate plume effects over a large region and long time span, providing for a relative ranking of pollution impacts on coastal areas. Clearly, site-specific or short-duration inputs will require dedicated, localized effort beyond this long-term, regional-scale PEI approach.

Extent of Plumes and Pollutant Exposures

In this study, we identified at least 2,400 sq km of nearshore waters and approximately 320 km of coastline between San Diego and Ventura County that could potentially be affected by discharge plumes that emanate from either wastewater treatment plants or rivers. About 15% of this area experiences plumes from both sources, making cumulative impacts of anthropogenic influences an important management concern. As expected, areas where plumes overlap also tend to be some of the most highly populated, accessible, and utilized portions of the coastline. Santa Monica and San Pedro Bays receive both treated effluent and riverine runoff from large urbanized areas of the greater Los Angeles Basin, making them two of the most highly impacted areas of the SCB.

The distribution of PEIs throughout the SCB indicates that the majority of California state waters within the SCB remain relatively unaffected by anthropogenic pollutants from these sources. Of the 1,986 sq km of state waters affected by plumes, 45% have a PEI of <3, while only 4.2% have a PEI of ≥ 8 . However, areas with a higher PEI are generally closer to shore and, therefore, more likely to impact both sensitive habitats and areas used for human recreation.

Comparison of Relative Risk from Each Source

The risk from POTWs and rivers varies both temporally and spatially. Treated wastewater discharge from POTWs is a continuous process that discharges pollutants to coastal waters on a more consistent basis. Conversely, the extent and volume of river discharge is directly proportional to precipitation events, resulting in intermittent and somewhat unpredictable plume extent and duration. Subsequently, river plume extent was generally smaller than the POTW plume extent. However, river plumes tend to remain inshore of the 30 m isobath, while POTW plumes occur most frequently between the 30 m and 60 m contours. Therefore, pollutants from river plumes are more likely to settle in nearshore sediments or be retained within very shallow waters, potentially causing greater impacts on marine ecosystems (Bay et al. 2003). POTW plumes, though persistent and widespread, emerge from outfalls near the ocean bottom (approximately 60 m) and tend to remain trapped below the upper mixed layer, mixing into larger volumes of water. Ultimately, this condition decreases the likelihood that POTW discharges will affect shallower habitats. However, wastewater plumes are more likely to impact offshore ecosystems (Howard et al. 2014).

Our sensitivity analysis indicated that in wet years, river plumes can contribute up to five times the pollutant load of dry years and potentially impact 10 times the area, while inputs from sewage discharge remain relatively similar. For this reason, it is important to use multiple years of runoff

and loading data (at least 10, as in this study) to capture long-term patterns in pollutant exposure. Although smaller time scales can be modeled using our approach, the accuracy of the model as a predictor of overall exposures would be limited.

Role of PEI in Research and Management

Our development of a spatially referenced PEI for the SCB provides a means to easily and rapidly compare relative anthropogenic threats to a variety of ecosystems. It relies on underlying datasets that model the intrusion and dispersal of freshwater plumes and pollutants into the marine environment. The index provides a simplified, long-term average, and inherently loses some of the accuracy of intensive studies that examine plumes over smaller areas and time scales. However, by integrating multiple sources of data, our PEI provides a synoptic look at coastal water quality, providing environmental management agencies the ability to rank and prioritize affected habitats in terms of susceptibility and management opportunities.

The PEI has many implications for mitigation and management practices designed to protect both the integrity of coastal ecosystems and human health. Since enactment of the Clean Water Act in 1972 and subsequent environmental legislation that explicitly recognizes the connections between anthropogenic pollutants and ocean health, our understanding of these connections has continually been strengthened by research. This PEI continues the trend by directly linking land-based loads of nutrients, metals, and sediments that arise from multiple individual sources to ocean circulation patterns. The links can be manipulated to model how upstream changes in land use, flood control and drainage infrastructure, and runoff mitigation attempts might affect loadings on an individual parameter basis. For example, if new regulations require POTWs to change how they process effluent to meet new permitting standards, the downstream effects of those changes can be easily predicted using our tools.

Future Directions

We are aiming to use and modify the PEI in several aspects. The first direction is to examine the PEI within a new AOI. There are 27 new or modified marine protected areas (MPAs), comprising approximately 15% of the SCB coastline (including the Channel Islands), that specifically limit fishing and other extractive activities (California Department of Fish and Wildlife 2013). Little is known about the effect of water quality in these MPAs, and the new index is one avenue for ascertaining risk and prioritizing future resources to characterize problems in MPA performance.

A second new direction is to examine additional sources of pollutants. Two potentially important sources are small POTWs and runoff from small urbanized coastal catchments. We examined the four largest POTWs in the SCB, but there are seven small POTW outfalls that, despite being only a fraction of the four large POTWs examined herein, may have discrete local impacts. Unfortunately, the plume mapping for these small POTWs is lacking (Jones et al. 2011), and we chose not to extrapolate limited results or large POTW plumes to unmapped small POTW outfalls. Similarly, urban runoff that directly enters the ocean through small creeks and coastal storm drains can be a major localized source of pollution. More storm drain water-quality datasets are becoming available through municipal and volunteer monitoring programs (for example, Los Angeles Department of Public Health, LA Waterkeeper, and City of San Diego all have regular storm drain monitoring projects). However, there is little available long-term data on the dispersal of these pollutants once they enter the ocean. With the advent of new plume monitoring methods such as gliders, it may become easier and less expensive to map the effects of these sources.

A third new direction is to incorporate differential dispersal patterns in the modeled parameters (Reifel et al. 2009). We treated each of the three pollutants as though they were conservative tracers of the plume; and therefore, their concentrations decrease linearly with distance from the plume source. However, it is likely that they are not true conservative tracers of freshwater transport. For example, TSS typically settles more rapidly than nitrate is diluted. The result would be a higher rate of TSS loss from the plume. Prediction of TSS exposure in the nearshore environment is also complicated by processes other than riverine and POTW discharges. In particular, the resuspension of sediments by high wave energy and currents near headlands can result in high TSS exposures that are not accounted for in this study. By adjusting dilution factors for each pollutant to more accurately reflect true oceanographic conditions, accuracy of the model can be further improved for TSS. Likewise, nitrate is typically consumed relatively rapidly by phytoplankton, and these dynamics are not intrinsic to the PEI. To enhance the plume extent portion of the PEI, additional dispersion, advection, or transformation models can be applied. This would allow for more accurate estimates of potential secondary effects, if necessary.

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Supplemental Resources

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The digital content for this chapter, explained as follows in this section, can be found in the book's online resources (esri.com/esripress-resources/ocean-solutions-2e).

Plume Interpolation Scripts

Python scripting was indispensable in completing the analyses described in this chapter. We simplified multiple geoprocessing steps using a combination of ArcPy and ModelBuilder and individual geoprocessing tools available in ArcGIS. In particular, we sought to automate the interpolation of pollutant plumes, clipping them to polygonal boundaries, and preparing to sum them together to calculate the pollutant exposure index.

Examples of two of these scripts are provided in the supplemental materials, along with a subset of the data used in our analysis. Both scripts take advantage of a variety of ArcGIS Spatial Analyst functions. Please see the `readme.txt` file included with the scripts for instructions on saving and running these scripts using the sample data.

The first script, `IDW_plume.py`, interpolates pollutant load values across the point feature classes that represent individual modeled plume grids. The script uses the same spatial extent and interpolation variables for each grid to ensure that they are consistent and can be summed together after additional processing. The second script, `Clip_IDW_by_plume_boundaries.py`, modifies the output rasters from the first script. This script extracts plume raster values using individual boundary polygons that describe the actual extent of each plume (as determined in the model used to create the plume extents). In this step, all values within the rectangular extent of the raster that fall outside the plume boundary are set to NoData by default. Next, it sets NoData values in each raster to zero, so the individual plume rasters may be summed into a single integrated pollutant load raster.

Once these two scripts were executed and all interpolated plumes were processed, we used additional geoprocessing tools to sum together the set of plumes for each pollutant and create the pollutant exposure index from these summed plumes. Because these subsequent steps were carried out a limited number of times, we did not develop scripts to automate them.

CHAPTER 7

Development of a Map Viewer for Archipelago de Cabrera National Park, Balearic Islands, Spain

Beatriz Ramos López, Nuria Hermida Jiménez, and Olvido Tello Antón

Abstract

This chapter describes the development of a map viewer (accessible in Spanish at <http://www.ideo-cabrera.ideo.es>) for the Archipelago de Cabrera National Park, Balearic Islands, Spain. The park is a region with various forms of protection, which demonstrates the importance of this area and the need to expand knowledge about it and facilitate the management and monitoring of a wide range of environmental threats and hazards. The development of the map viewer (leveraging ArcGIS Viewer for Flex software) is one of the pioneering initiatives in Spain that relates GIS technology to the marine environment. It is the result of extensive interinstitutional collaboration between the EU-US Marine Biodiversity research group of the Instituto Franklin-Universidad de Alcalá, the Instituto Español de Oceanografía, and the Organismo Autónomo de Parques Nacionales. Keywords for this chapter include *GIS, web mapping, map viewer, Visor, metadata, WMS, INSPIRE, ArcGIS, geoportal, Cabrera, parque nacional, national park, Islas Baleares, Balearic Islands, España, Spain*.



Part of Archipelago de Cabrera National Park, south of Mallorca, one of the Balearic Islands east of Spain.
Photo by Beatriz Ramos López.

Introduction

The merger of GIS and the Internet has led to a revolution of sorts since its inception in 1993 (Fu and Sun 2011), and particularly with the World Wide Web becoming a popular vehicle for the distribution of myriad sources of information. Web-based GIS has quickly evolved accordingly (Shekhar et al. 2001). Indeed, the web has changed the perspective on the role that maps can play (Kraak 2004; Shekhar and Xiong 2008), affecting both the users and developers of GIS, as well as society as a whole. One of the most important advances in GIS is a reliance on web mapping to share and visualize large amounts of data, particularly in the areas of spatial data access, geovisualization and exploration of data, and data processing (Dragicevic 2004). Accordingly, Web 2.0 is a term used to represent the many changes brought forth by software developers and users who interact with the web, making it more interactive, social, and customizable.

Web 3.0 is within reach (Strickland 2008), particularly through the use of more participatory mapping and the recent exchange and flow of data in the cloud. In this vein, web GIS has the potential to make data and information easily accessible to users with limited knowledge of GIS (e.g., Merrifield et al. 2013) and tailor it to specific topics (e.g., wetlands, coastal hazards, and marine protected areas, or MPAs), along with providing support for environmental decision-making and the proposal of new research projects (Mathiyalagan et al. 2005; Boroushaki and Malczewski 2010).

This chapter seeks to highlight the importance of web GIS technologies as an essential tool in the marine world. Several recent international directives support conservation of the marine environment, and technologies such as GIS are helping to make this goal possible.

Among the most important is Chapter 17 of the United Nations Agenda 21, which reiterates that the well-being of coasts and oceans is of global concern. In addition, the European Union (EU) Water Framework Directive of December 2000 is regarded as the most important legal stimulus at the EU level for integrated planning, both coastal and inland (Connolly and Cummins 2002). The UN Millennium Declaration of 2000 inspired the design and operation of integrated freshwater and marine management. The World Summit on Sustainable Development in 2002 outlined a broad thematic approach to coastal and ocean management (Vallega 2005). In 2007, the European Union launched an Integrated Maritime Policy, in parallel with the Infrastructure for Spatial Information in the European Community (INSPIRE) Directive (European Commission 2014a) and European Spatial Data Infrastructure (ESDI). In 2008, the Marine Strategy Framework Directive (MSFD) (European Union 2008), another environmental pillar for European maritime policy, was established to greatly improve the environmental status of European seas by 2020, including the creation of a multiresolution digital map from seabed to sea surface (Meiner 2010). In March 2013, the European Commission proposed legislation to create a common framework for maritime spatial planning (MSP) and integrated coastal zone management (European Commission 2012; European Commission 2014a, 2014b).

The preceding directives and initiatives show the continued importance of protecting the oceans and the many resources and benefits they provide, as well as the importance of GIS in helping achieve these aims (see also Serral et al. 2009). The creation of the map viewer described in this chapter is a response to the implementation of many of these requirements, with a specific focus on revealing unknown aspects of the Archipelago de Cabrera National Park, Balearic Islands, Spain, along with a geospatial tool for managers to aid in the park's planning and management.

Spatial Data Infrastructure and Geoportals

Portugal was an early pioneer in terms of European spatial data infrastructure (SDI) conceptual and operational developments, but at present Spain is one of the most active countries on this front. Both countries are actively involved in developing their own national SDIs, focusing, like every EU country, on meeting INSPIRE requirements and national needs (Julião et al. 2009). According to the *Instituto Geográfico Nacional* (IGN), the official definition of an SDI for Spain is an integrated computer system that (1) shows a set of resources (e.g., catalogs, servers, software, data, applications, and websites); (2) is dedicated to managing geographic information (e.g., geographic information maps, orthophotos, satellite images, and place-names); (3) provides resources online while also meeting a number of conditions for interoperability (i.e., standards, specifications, protocols, and interfaces); and (4) allows users of many types and backgrounds to combine various resources according to his or her needs. As such, SDIs aim to catalog and make available to the general public all the information that is often unknown or does not have proper channels for release (Capdevila i Subirana 2004).

The Spanish National Spatial Data Infrastructure (IDEE for *Infraestructura de Datos Espaciales de España*) began in 2002 and was coordinated by the National Geographic High Council, a governmental body composed of representatives of producers of reference and thematic digital geographic data at the national level by agencies such as the National Geographic Institute, Ministry

of Agriculture, Cadastre, and so forth; at the regional level by Cartographic Institutes and Regional Services of Cartography; and at the local level. The geoportal of the Spanish national SDI was launched in July 2004 (Julião et al. 2009).

Geoportals such as this one organize content and different services such as directories, information resources, data, and applications (Maguire and Longley 2005). One of the earliest marine SDIs in Spain, SIG Pesca, was developed by the *Dirección General de Pesca y Acción Marítima de la Generalitat de Catalunya* in 2008 using the software Miramon (Almazán et al. 2009).

In addition, metadata is one of the most important keys to the discovery of geospatial information as part of an SDI (Ballari et al. 2006; Takken 2008). The benefits of having metadata as a record are many: (1) it provides an inventory of the data; (2) it helps determine and maintain the value of the data; (3) it helps determine the reliability and timeliness of the data; (4) it can serve as documentation with legal grounds; and (5) it helps maintain and verify accuracy to support good decision-making and cost savings (Esri 2003).

The aim of geoportals is to be interoperable with each other, but a primary obstacle is the lack of standard exchange mechanisms for sharing both data and metadata and facilitating access to the general public (*La Infraestructura de Datos Espaciales de España* 2014; Julião et al. 2009). Recent efforts by the Open Geospatial Consortium (OGC) (2014) have resulted in several specifications to alleviate these problems. The OGC Web Map Service (WMS), as well as Geographic Markup Language (GML), are such standards for developing interoperable web GIS. With the demand for geospatial interoperability and adoption of open standards, GIS is evolving from traditional client-server architecture to web service architecture (Zhang and Li 2005).

The geoportal of the *El Instituto Español de Oceanografía*, or IEO (2014b) (figure 7.1), hosts an important part of Spain's SDI. IEO adopted the INSPIRE Directive as a mandatory component for developing an interoperable SDI, both for Spain and the broader European Union. Within the IEO geoportal, OGC WMS has been created to facilitate access to data and includes three kinds of requests: (1) *Get Capabilities* to return information via Extensible Markup Language (XML); (2) *Get Map* to return a map; and (3) *Get Feature* to return information associated with the map. Certain free GIS programs such as gvSIG are not able to handle WMS 1.3.0, so the IEO geoportal includes WMS 1.1.1 as well. An important feature of the geoportal is that metadata records for the datasets, as well as for WMS services, were created under the INSPIRE Directive.



Inicio

El Instituto Español de Oceanografía (IEO) es un organismo público de investigación (OPI), dependiente del Ministerio de Economía y Competitividad, a través de la Secretaría de Estado de Investigación, dedicado a la investigación en ciencias del mar, especialmente en lo relacionado con el conocimiento científico de los océanos, la sostenibilidad de los recursos pesqueros y el medio ambiente marino. El IEO representa a España en la mayoría de los foros científicos y tecnológicos internacionales relacionados con el mar y sus recursos.

Geoportal ofrece formas fáciles y convenientes de compartir datos geoespaciales.

The screenshot displays the IEO geoportal interface. On the left, under the heading 'Simplemente, puede...', there is a section titled 'Encontrar Metadatos'. It features a search input field containing the text 'cabrera', a 'Buscar' button, and the text 'Buscar Metadatos' below. On the right, under the heading 'Puede hacer más...', there is a section with the IEO logo and a list of actions: 'Visores', 'Compartir metadatos', 'Crear metadatos', 'Cargar metadatos', and 'Publicar metadatos'.

Figure 7.1. Screen capture of the El Instituto Español de Oceanografía (IEO) geoportal, based on Esri Geoportal Server software. Image © 2013 Instituto Español de Oceanografía (Spanish Oceanographic Institute); used by permission.

The Map Viewer

The map viewer for the Archipelago de Cabrera National Park (hereafter referred to as the “Cabrera map viewer”) is accessible in Spanish at <http://www.ideo-cabrera.ieo.es> and located within the IEO geoportal. It seeks to integrate physical and chemical parameters and biological data. It integrates all these parameters to facilitate the understanding of the characteristics of the national park to aid the decision-making of managers and scientists, as well as provide a better knowledge of the park for the general public. The Archipelago de Cabrera National Park (figure 7.2), located south of the island of Mallorca within the Balearic Islands, is one of the 15 national parks of Spain. The park was established in 1991 with an acreage of 10,021 (8,703 terrestrial and 1,318 marine).

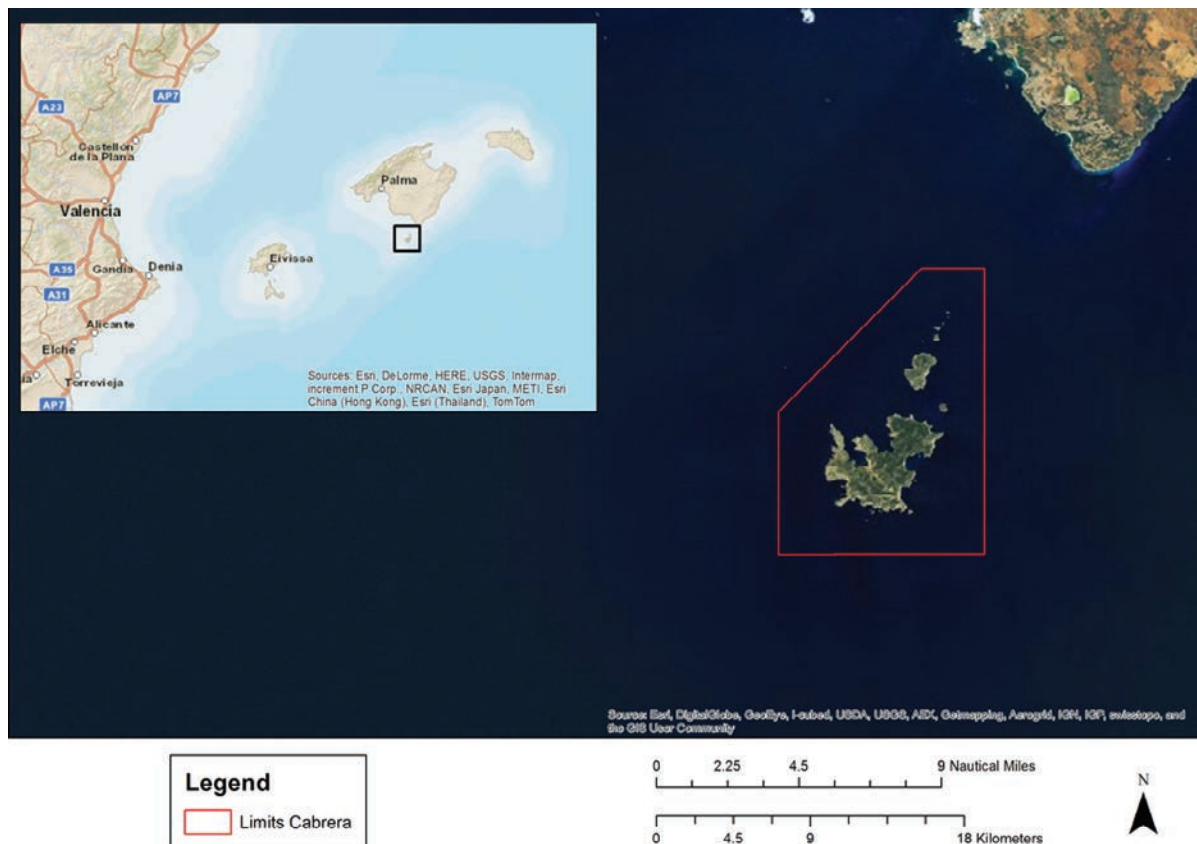


Figure 7.2. Location map of the Archipelago de Cabrera National Park. Map data sources: Inset map “World Street Map”: Esri, DeLorme, HERE, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), and TomTom. Larger map: “World Imagery” map: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Map Viewer Benefits

In general, tools such as the map viewer for the Archipelago de Cabrera National Park hold several benefits as a fundamental management tool for MPA management, integrated coastal area management, and marine spatial planning. A map viewer can also offer a general vision of the projects, protection sites, and biological information of Cabrera that is of great utility for stakeholders.

In addition, a map viewer offers an important window into an unknown, relatively unexplored world. Whereas the exploration of outer space is well under way and almost every piece of land on Earth has been discovered and mapped, not much is known about the world’s oceans that cover ~70% of the earth’s surface and harbor many biological species (see Vermeulen 2013). With only 5% to 10% of the world’s ocean floors mapped with the resolution of similar studies on land (Sandwell et al. 2003; Wright 2003), marine geomorphology still represents a persistent gap in our knowledge (Wright and Heyman 2008). Despite the high appraisals of the potential of GIS applications in coastal and marine environments, the development of coastal GIS is still challenged by (1) the complexity of highly dynamic coastal and marine systems in a three-dimensional environment, (2) the lack of data worldwide, and (3) the lack of communication between coastal experts and GIS professionals (Green 1995; Hooge et al. 2001; Zeng et al. 2001; Mujabar and Chandrasekar 2010).

Technical Objectives and Approach

The technical objectives of the project included facilitating (1) the search for all available datasets about the park and their subsequent organization into a geodatabase; (2) literature reviews for park resource management and research projects; (3) the creation of maps and WMS services (versions 1.1.1 and 1.3.0) using ArcGIS for Server; (4) the development of metadata in compliance with the INSPIRE Directive; and (5) the deployment of an effective geospatial system for researchers, managers, and the general public. The Cabrera map viewer is based on several technologies, including ArcMap, ArcCatalog, and ArcGIS for Server 10.1 software for backend data development and hosting on the ArcGIS platform; Esri Geoportal Server software for serving metadata and WMS services; Adobe Flash Builder 4.6 for programming; and ArcGIS Viewer 3.3 for Flex for final map viewer deployment.

The first phase of the project was to locate the data to be displayed in the Cabrera map viewer, such as that of the *Banco de Naturaleza* of *Ministerio de Agricultura, Alimentación y Medio Ambiente* (MAGRAMA) (2014a, 2014b). Other data, such as fisheries and bathymetry, came from services created by the IEO (2014c, 2014d). Still other layers were contributed by nongovernmental organizations (NGOs) such as Oceana.

The next step was the creation of a Cabrera file geodatabase (.gdb), with a geodetic reference system of European Terrestrial Reference System 1989 (ETRS 89), Universal Transverse Mercator (UTM) Zone 31 (using a spatial reference of European Petroleum Survey Group, or EPSG, projection 25831). Several groups of feature dataset layers were created using their respective feature classes, grouped into five themes: Protection, Limits, Bathymetry, Biological Data, and Videos. Relationship classes and topology rules were built between the layers.

Next, map services and geoprocessing services were created using ArcGIS for Server. All layers were published together as a representational state transfer (REST) map service, as well as within an ArcMap map document (.mxd) project file. The geodatabase was also mirrored by another server named IDEO2, which was protected against external attacks and in which ArcSDE software was used to manage the Microsoft SQL Server enterprise geodatabase. A REST-style printing service was developed to adapt a new template named printCabreraA3Land, which was created in ArcMap and subsequently exported to the IEO server.

WMS 1.3.0 was created in ArcGIS for Server to enable the WMS capability at the same time that we published the map service. As mentioned earlier, WMS 1.1.1 was also created to offer more possibilities to users, expanding the Get Capabilities of both.

INSPIRE-compliant metadata records were created for both the data and WMSs. After creating the metadata in the IEO geoportal, the records were validated on the INSPIRE Geoportal Metadata Validator site (European Commission 2014b).

The next step was to develop the Cabrera map viewer itself, using ArcGIS Viewer 3.3 for Flex. The aim of Adobe Flex programming technology is to offer web developers a tool to quickly and easily build rich Internet applications (RIAs). The Adobe Flash Integrated Development Environment (IDE) was used concurrently while developing in the Flex Viewer. Operational layers of IEO services were configured as map services. Several widgets were configured to provide functionality in the map viewer display, especially to make it easy for users of many skills and backgrounds to interact with the viewer. These widgets (figure 7.3) include

- *Legend*, showing the symbols assigned to each layer to facilitate their interpretation
- *Print*, allowing for download of a map of the chosen area, transformed into different formats for saving and printing
- *Search* (eSearch), with multiple options for searching between layers in the display

- *Edition* (Draw), allowing the user to draw or measure on the map
- *Links*, allowing access to external resources such as a photo album about Cabrera on Flickr, the IEO geoportal, or to websites for those wishing to visit the Archipelago de Cabrera National Park
- *Bookmarks*, to facilitate navigation among three principal zones: Spain, the Balearic Islands, and Archipelago de Cabrera National Park
- *Location*, to enter coordinates or orient the map in different directions
- *Attribute table*, new in ArcGIS Viewer 3.3 for Flex, allowing display of an attribute table for a selected layer directly in the map viewer
- *Chart*, for charting infauna data (benthic organisms that live buried within sedimentary layers of the seabed)



Figure 7.3. Screen capture of the map viewer of Archipelago de Cabrera National Park, showing the various widgets available. Image © 2013 Instituto Español de Oceanografía (Spanish Oceanographic Institute); used by permission.

To offer more map interactivity, pop-up windows with additional detail, including photos of marine mammals and other species, are available when a user selects an object. Once the tools and layers were integrated, the entire project was compiled in Adobe Flash Builder. The final Cabrera map viewer is available at <http://www.ideo-cabrera.ideo.es> (figure 7.4). Accompanying metadata, in WMS 1.3.0 and 1.1.1, is shown in figures 7.5, 7.6, and 7.7 (IEO 2014b).



Figure 7.4. Screen capture of the map viewer of Archipelago de Cabrera National Park. Image © 2013 Instituto Español de Oceanografía (Spanish Oceanographic Institute); used by permission.



Figure 7.5. Screen capture of metadata records associated with the map viewer of Archipelago de Cabrera National Park. Image © 2013 Instituto Español de Oceanografía (Spanish Oceanographic Institute); used by permission.

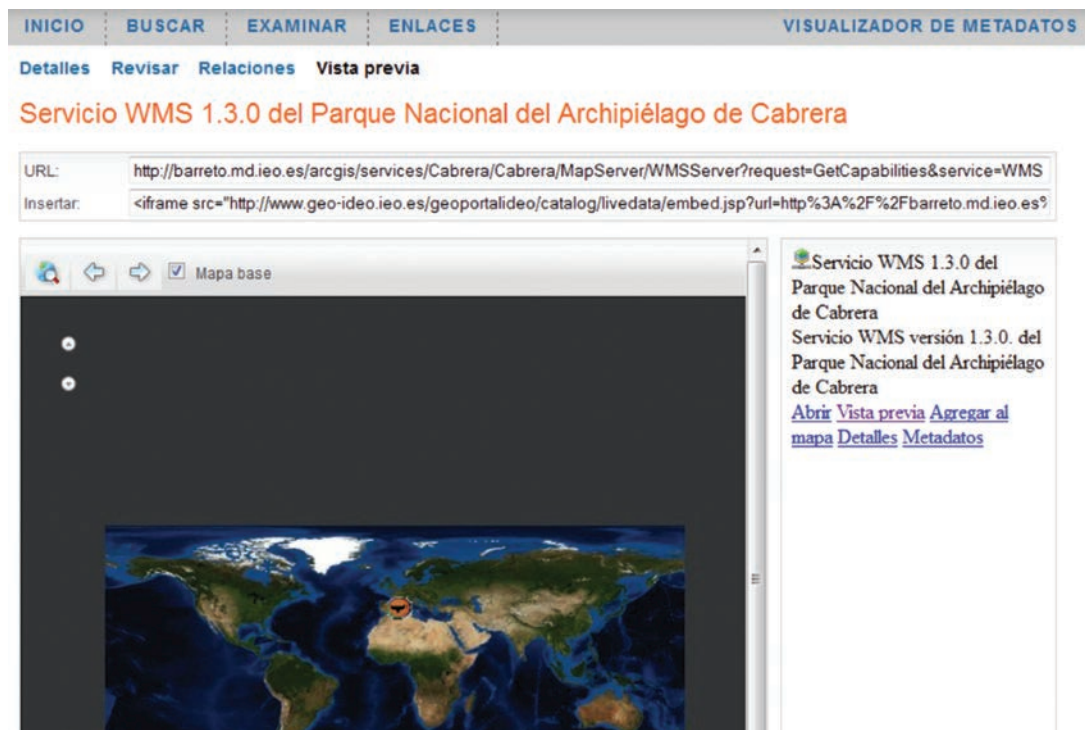


Figure 7.6. Screen capture of WMS 1.3.0 and metadata associated with the map viewer of Archipelago de Cabrera National Park. Image © 2013 Instituto Español de Oceanografía (Spanish Oceanographic Institute); used by permission.



Figure 7.7. Screen capture of WMS 1.1.1 and metadata associated with the map viewer of Archipelago de Cabrera National Park. Image © 2013 Instituto Español de Oceanografía (Spanish Oceanographic Institute); used by permission.

The Cabrera map service and geoprocessing service descriptions are shown in figures 7.8 and 7.9 (IEO 2014a, 2014b). The Get Capabilities in WMS 1.3.0 and 1.1.1 are shown in figures 7.10 and 7.11, respectively (IEO 2014f, 2014e).

ArcGIS REST Services Directory [Login](#) | [Get Token](#)

[Home](#) > [services](#) > [Cabrera](#) > [Cabrera \(MapServer\)](#) [Help](#) | [API Reference](#)

[JSON](#) | [SOAP](#) | [WMS](#)

Cabrera/Cabrera (MapServer)

View In: [ArcGIS JavaScript](#) [ArcGIS.com Map](#) [Google Earth](#) [ArcMap](#) [ArcGIS Explorer](#)

View Footprint In: [ArcGIS.com Map](#)

Service Description: Visor del Parque Nacional del Archipiélago de Cabrera

Map Name: Layers

[Legend](#)

[All Layers and Tables](#)

Layers:

- [Limites](#) (0)
 - [Limites Parque Nacional Archipiélago Cabrera](#) (1)
- [Videos](#) (2)
 - [VideosOAPN](#) (3)
- [Batimetría](#) (4)
 - [Batimetría Maestras](#) (5)
 - [Batimetría](#) (6)
- [Figuras de Protección](#) (7)
 - [ZEPA Archipiélago de Cabrera](#) (8)
 - [LIC Archipiélago de Cabrera](#) (9)
 - [IBA Sur de Mallorca](#) (10)
 - [ZEPIM Archipiélago de Cabrera](#) (11)

Figure 7.8. Screen capture of the map service description for the map viewer of Archipelago de Cabrera National Park. Image © 2013 Instituto Español de Oceanografía (Spanish Oceanographic Institute); used by permission.

ArcGIS REST Services Directory [Login](#) | [Get Token](#)

[Home](#) > [services](#) > [Cabrera](#) > [printCabreraA3Land \(GPService\)](#) [Help](#) | [API Reference](#)

[JSON](#) | [SOAP](#)

Cabrera/printCabreraA3Land (GPService)

Service Description: This tool takes the state of a web application (for example, included services, layer visibility settings, and client-side graphics) and returns a printable page layout or basic map of the specified area of interest. The input for Export Web Map is a piece of text in JavaScript object notation (JSON) format describing the layers, graphics, and other settings in the web map. The JSON must be structured according to the ExportWebMap specification in the ArcGIS Help. This tool is shipped with ArcGIS Server to support web services for printing, including the preconfigured service named PrintingTools. The ArcGIS web APIs for JavaScript, Flex and Silverlight use the PrintingTools service to generate images for simple map printing.

Tasks:

- [Export Web Map](#)

Execution Type: `esriExecutionTypeAsynchronous`

Result Map Server Name:

MaximumRecords: 1000

Child Resources: [Info](#)

Figure 7.9. Screen capture of the geoprocessing service description for the map viewer of Archipelago de Cabrera National Park. Image © 2013 Instituto Español de Oceanografía (Spanish Oceanographic Institute); used by permission.

Este fichero XML no parece tener ninguna información de estilo asociada. Se muestra debajo el árbol del documento.

```
<WMS_Capabilities version="1.3.0" xsi:schemaLocation="http://www.opengis.net/wms http://schemas.opengis.net/wms/1.3.0/capabilities_1_3_0.xsd http://www.esri.com/wms http://barreto.md.ieo.es/arcgis/services/Cabrera/Cabrera/MapServer/WmsServer?version=1.3.0%26service=WMS%26request=GetSchemaExtension">
  <Service>
    <Name>WMS Cabrera</Name>
    <Title>
      Servicio WMS del Visor del Parque Nacional del Archipiélago de Cabrera
    </Title>
    <Abstract>
      Servicio WMS versión 1.3.0. del Parque Nacional del Archipiélago de Cabrera
    </Abstract>
    <KeywordList>
      <Keyword>
        WMS,Cabrera,visor,Islas Baleares,Balearic Islands,España,Spain,National Park,Parque Nacional,AMP,MPA
      </Keyword>
    </KeywordList>
    <OnlineResource xlink:type="simple" xlink:href="http://barreto.md.ieo.es/arcgis/services/Cabrera/Cabrera/MapServer/WmsServer?"/>
  </Service>
  <ContactInformation>
    <ContactPersonPrimary>
      <ContactPerson>Beatriz Ramos López</ContactPerson>
    </ContactPersonPrimary>
    <ContactOrganization>
      Instituto Franklin-Universidad de Alcalá de Henares (IF-UAH)
    </ContactOrganization>
    <ContactPersonPrimary>
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      <AddressType></AddressType>
    </ContactAddress>
  </ContactInformation>

```

Figure 7.10. Screen capture of WMS 1.3.0 Get Capabilities of the map viewer of Archipelago de Cabrera National Park. Image © 2013 Instituto Español de Oceanografía (Spanish Oceanographic Institute); used by permission.

```
WMSServer.esri.map: Bloc de notas
Archivo Edición Formato Ver Ayuda
?xml version="1.0" encoding="UTF-8"?
<WMT_MS_Capabilities version="1.1.1">
  <Service>
    <Name>[CDATA[WMS Cabrera]]</Name>
    <Title>Servicio WMS del visor del Parque Nacional del Archipiélago de Cabrera</Title>
    <Abstract>Servicio WMS versión 1.1.1. del Parque Nacional del Archipiélago de Cabrera</Abstract>
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      <Keyword>[CDATA[Cabrera]]</Keyword>
      <Keyword>[CDATA[Parque Nacional]]</Keyword>
      <Keyword>[CDATA[National Park]]</Keyword>
      <Keyword>[CDATA[visor]]</Keyword>
      <Keyword>[CDATA[Islas Baleares]]</Keyword>
      <Keyword>[CDATA[Balearic Islands]]</Keyword>
      <Keyword>[CDATA[España]]</Keyword>
      <Keyword>[CDATA[Spain]]</Keyword>
    </KeywordList>
    <OnlineResource xmlns:xlink="http://www.w3.org/1999/xlink" xlink:type="simple" xlink:href="http://barreto.md.ieo.es/arcgis/services/Cabrera/Cabrera/Maps">
  </Service>
  <ContactInformation>
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      <ContactPerson>[CDATA[Beatriz Ramos López]]</ContactPerson>
    </ContactPersonPrimary>
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```

Figure 7.11. Screen capture of WMS 1.1.1 Get Capabilities of the map viewer of Archipelago de Cabrera National Park. Image © 2013 Instituto Español de Oceanografía (Spanish Oceanographic Institute); used by permission.

Concluding Remarks

The development of the Cabrera map viewer was an interesting exercise in data integration and map interface design, with an eye toward assisting managers and researchers not only in more fully understanding the resources of the park, but also in envisioning its possible enlargement. The Cabrera map viewer seeks to encourage best practices of data management in the context of the INSPIRE Directive and, as new technology breakthroughs aid in handling huge amounts of data (big data), in better visualizing the ocean in three dimensions and managing the ocean via geodesign. The hope is that many new datasets will be made available to the map viewer as the project continues.

In addition, it was gratifying to develop an important dissemination tool to help the general public better understand the richness and importance of this relatively unknown protected area, visit the area, and participate in public events there. It is hoped that with such knowledge of this region, the public will also be motivated to advocate for conservation of other marine environments.

Acknowledgments

We are thankful to several organizations for providing the datasets that were integrated into the Cabrera map viewer, including the *Organismo Autónomo Parques Nacionales* (OAPN), IEO, Oceana, and MAGRAMA. We would like to acknowledge the contribution of Paula Alonso for valuable support in translating this chapter from Spanish to English, and to book editor Dawn J. Wright for subsequent editing. The comments and suggestions of two anonymous reviewers greatly improved this chapter.

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CHAPTER 8^{Updated}

Whale mAPP: Engaging Citizen Scientists to Contribute and Map Marine Mammal Sightings

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Abstract

Traditional methods of gathering and managing data to map marine mammal distributions requires extensive time and resources. Therefore, a GIS solution was developed using a volunteered geographic information approach. Whale mAPP consists of mobile and web apps that allow anyone to submit and visualize observations. An Android mobile app, developed using the ArcGIS Runtime software development kit for Android application programming interface, uses Global Positioning System-enabled smartphones to record sightings, animal behavior, and weather; track and display survey paths; and collect photographs, which are transmitted to a geodatabase through a feature service. The web app, developed using the ArcGIS API for JavaScript, allows both the public and researchers to query observations and download data in shapefile format. Curricular materials with conservation themes are designed for middle-school students and use ArcGIS Online service to help improve spatial literacy. The additional data collected by users of Whale mAPP will supplement the knowledge base on marine mammal distributions to contribute to research and management efforts.

Introduction

Understanding Human Impacts on Marine Mammals

The majority of people worldwide live within a short distance of the ocean, yet many are surprisingly unaware of the animals that make our coasts their home. Marine mammals can serve as charismatic megafauna to entice people to make an effort to learn more about marine life and to value conservation concerns. Unfortunately, many of the species are endangered or threatened, and baseline data is lacking for most populations. Healthy populations of marine mammals serve as a draw to tourists and locals alike. For example, in California millions of people observe whales from

boats or shore every year (Hoyt 2000). Encounters are often photographed or video recorded, yet this information is rarely shared with anyone beyond social media users. Currently, researchers and managers have no way to access this untapped resource. This lack of access was the catalyst for the development of Whale mAPP, a citizen science–based web and mobile data collection platform built on the foundation of GIS.

Marine mammals are a diverse group of animals that are defined as mammals that rely on the marine habitat. They consist of three mammalian orders: *Carnivora* includes seals, sea lions, walruses, polar bears, and otters; *Cetacea* includes whales, dolphins, and porpoises; and *Sirenia* includes the dugongs and manatees. There are approximately 130 extant species of marine mammals worldwide (Committee on Taxonomy 2014).

Marine mammals are found throughout the world's oceans, inhabiting polar, temperate, and tropical regions. Species richness peaks at latitudes of 40, areas of high oceanic productivity (Schipper et al. 2008). Modeling of habitat preference based on surveys of species' presence/absence is increasingly used to identify important predictor variables (Gegr et al. 2013). Common parameters used in these models include bathymetry (depth and slope) and sea surface temperature (SST), both indicators of primary productivity (Kaschner et al. 2006; Becker et al. 2012). Many populations are known to inhabit productive coastal waters along the continental shelf and are thus especially susceptible to threats caused by growing human populations.

There is substantial concern about the conservation of marine mammals, as an estimated 36% of species are considered threatened (Schipper et al. 2008). The exact number of threatened species is difficult to determine because of the challenges associated with surveying animals that spend most of their time out of view and are distributed over a large geographic area. As a result, the number of threatened species ranges between 23% (includes only species with sufficient data) and 61% (if all data-deficient species are threatened) (Schipper et al. 2008). Many populations were historically decimated by whaling, and some, such as the Atlantic gray whale population, were even extirpated (Mead and Mitchell 1984). After the International Whaling Commission placed a moratorium on commercial whaling in 1986, many species increased in number, yet modern populations of most species remain a fraction of their historical size (Roman and Palumbi 2003). Today, both subsistence and commercial harvesting continue to threaten 52% of species (Schipper et al. 2008). Other major threats include incidental mortality from fisheries bycatch and vessel strikes (figure 8.1), pollution (toxins and marine debris, figure 8.2), noise, and climate change (Schipper et al. 2008; Reynolds et al. 2009).



Figure 8.1. Humpback whale injury caused by boat propeller documented off the coast of California. Photo courtesy of Shane Keena Photography.



Figure 8.2. Sea lion entanglement off the coast of Southern California caused by marine debris. Photo courtesy of Shane Keena Photography.

Transforming Data Collection

The lack of reliable data on marine mammal populations makes conservation especially challenging. As the recent Gulf of Mexico oil spill has taught us, it is essential to have baseline marine mammal data to assess and mitigate damage caused by natural and anthropogenic-induced disasters. As Reynolds and colleagues (2009, 25) emphasize: “Science does play a crucial role in the conservation of marine mammals and ecosystems.” Gregr and colleagues (2013) describe the importance of modeling habitat use of marine mammals to improve our understanding of species ecology and critical habitat and ability to identify where animals and human threats may overlap. Research needs to focus on core biological questions regarding species distributions, associations, and movement patterns so that we can evaluate the impact of human disturbances.

Gathering this data on marine mammals is time consuming and resource intensive. Regulatory agencies, such as the National Oceanic and Atmospheric Administration (NOAA), collect sightings data from large-scale surveys following predesigned transects (Kinzey et al. 2000). These surveys provide essential data on species distribution and abundance but have decreased in frequency because of budget limitations. In addition, although NOAA surveys cover large geographical regions, many areas are still not surveyed seasonally on a regular basis. Taylor and colleagues (2007) analyzed monitoring data on marine mammal stocks within the United States to calculate that scientists will not be able to detect the vast majority of precipitous declines (defined as a 50% decrease in abundance over 15 years). They concluded that increasing survey extent and frequency

will improve the ability to detect declines but requires a substantial increase in funding. Researchers have begun to recognize the opportunity of numerous whale watchers and vessels that observe, and often even record, their opportunistic sightings (Palazzo et al. 2004). The difficulty has been in standardizing and sharing this potential wealth of data. With the technological advancements provided by mobile apps, citizen science can greatly expand our knowledge base to support conservation and management. The web and mobile app system Whale mAPP allows anyone equipped with a Global Positioning System (GPS)-enabled Android smartphone (version 4.1 and higher) to record their sightings and transmit that information to a geodatabase that is accessible to researchers and the public. An accompanying website (Stelle and King 2014) provides nearly instantaneous data on sighting locations, behavior, group size, and photographs of the species in an interactive format.

Why Citizen Science?

Citizen science, the involvement of interested members of the public in collecting and analyzing data for scientific projects, is not a recent phenomenon. One of the earliest examples is the National Audubon Society's annual Christmas Bird Count, ongoing since 1900. Contributions of bird watchers to the field of ornithology provides one of the greatest examples of citizen science; a recent survey described 10 projects run by Cornell Lab of Ornithology, which contribute over a million records a month (Bonney et al. 2009). Allowing citizens to participate in the scientific inquiry process may bring about awareness, empowerment, and stewardship. Additionally, the inclusion of citizen scientists may help reduce the gaps that have historically divided the public, researchers, and policy makers in environmental management efforts (Connors et al. 2011).

Goodchild (2007) coined the term “volunteered geographic information” (VGI) to describe geographic data provided voluntarily by individuals. The development of Web 2.0 and GPS and the rapid assimilation of mobile technology have made VGI practical. These technologies and the ability to quickly collect, transmit, and submit data is converting citizen scientists into citizen “sensors” (Catlin-Groves 2012). The use of mobile and web apps that use a VGI-based strategy in the collection of data in long-term environmental studies is a relatively new field. OakMapper, a working prototype of this data collection method, is a mobile- (iPhone) and web-based effort to encourage the public to help monitor the sudden oak death (SOD) of oak trees in California caused by the ramorum leaf blight virus (Geospatial Innovation Facility 2012). In addition, the Geyser Notebook 8 app for Android allows users to view information about the Yellowstone geysers and report eruption observations (Glennon 2014). However, there is no peer-reviewed published evidence that this app is used by researchers in understanding geyser activity in Yellowstone National Park. Yet as mobile VGI becomes more common, it is gaining acceptance as useful data by the scientific community. For example, a recent literature search by Catlin-Groves (2012) found over 300 peer-reviewed publications that included citizen science participation.

Whale mAPP provides a venue for the public, especially students, to become actively involved in valid scientific research. Volunteers are able to contribute sighting records via their mobile app or directly through the website and instantly see their results displayed in comparison to other contributors through the web app. They can easily click a point on the dynamic map and identify details about the sighting, along with additional information on the species. Video interviews and research summaries educate the user about threats to the various species, and a page dedicated to conservation efforts provides additional suggestions of actions that each individual can take to help protect the animals.

Engaging Users

Equally as important as the carefully crafted intention of Whale mAPP's role in citizen science and conservation efforts are its design and execution. User engagement is a key component of attracting and retaining data collectors. Fundamental to maintaining user engagement is providing an attractive, easy-to-use, and stable app. Web and mobile technologies have already been demonstrated as successful in a VGI-based study (Connors et al. 2011), and the technology is easy to use and familiar to most users. Apps that use these technologies were simultaneously developed to allow users to collect data without the need for an educational background in marine biology. Baseline testing is fundamental to ensuring an app's stability and is dependent on the profile of the user. However, Whale mAPP is intended for a broad cross section of users with variable background knowledge in marine biology, technology exposure, and geographic location. Because of this diversity of use, beta testing with a variety of users has become critical to Whale mAPP's success.

Mobile App

The Android platform was selected for initial development because of its worldwide popularity compared with its competitors. Specifically, the app was designed to work on versions of the Android operating system version 4.1 and later. The app was built to allow users to contribute track lines to document their efforts along with their marine mammal observations and to visualize both their track line and sightings while their trip is in progress.

When starting a trip from the home page, users are first asked to fill out a brief profile, including their login, boat type, and boat name. Upon entering pertinent trip detail information, users are presented with a map view (figure 8.3) in which they can visualize the survey as it is under way and record their observations. From this view, users can quickly access their camera by clicking the icon and zoom to their current location and explore the surrounding area by panning with their touch screen.

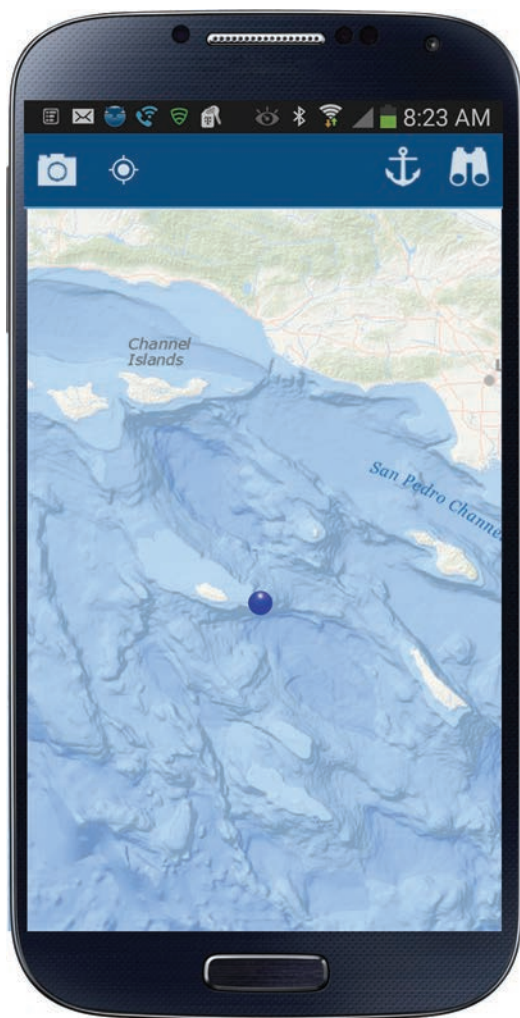


Figure 8.3. Map view displayed to the user throughout the trip using the Whale mAPP Android app provides access to the camera, current location, and the form for making observations (binoculars icon). Image by Whale mAPP © 2014. Data sources: Esri, GEBCO, NOAA, National Geographic Society, DeLorme, HERE, Geonames.org, and other contributors.

The target audience's cellular and GPS reception capabilities exhibit huge variability, especially when on vessels further offshore. Because of this variability, the Android app was designed to store data locally on the device and operate either in a connected or disconnected map mode. When operating in the connected mode, the app displays the user's track line and observations on top of the Esri Ocean Basemap; but when reception is not available, the user's track line and observations are displayed on either a blank canvas or basemaps previously downloaded by the user for a particular geographic extent.

When users choose to record an observation through the mobile app, they click the binoculars icon and get to a form that is based on datasheets used in research by both students and Earthwatch Institute volunteers (figure 8.4). The form, which focuses on monitoring the distribution and habitat use of marine mammal species in the Southern California Bight, captures the essential information on the species type, count, behavior, weather, and sea conditions. Additionally, it allows users to associate a photo with the observation and document their confidence in the observation on a scale of one to five (with one star for low confidence and five stars for high confidence). As users fill out the form, they can see their responses displayed before submitting the form. Giving users the room to fix mistakes in their observation details is an essential component of the user interface design (Norman 1988).

The figure shows a transition from a traditional paper form to a mobile app interface. On the left is a paper form titled 'Sightings, Tracking and Photographs' from the University of Redlands. It includes fields for date, time, location, vessel, and observer. The main section is a table with columns for 'TIME and PLACE', 'SPECIES', 'IMAGE LOG COMMENTS', and 'WEATHER'. Below the table is a legend for codes and species. On the right is a screenshot of the Whale mAPP mobile app. It shows a 'Select a category' screen with options for Whale, Dolphin, Seal, and Other. Below this is a 'Scroll to add details' section with options for 'Select a whale species', 'Specify a quantity', 'Presence of calves', 'Describe Behavior', 'Add a photo', 'Describe the weather', and 'Enter a note'. A large blue arrow points from the paper form to the mobile app interface.

Figure 8.4. The traditional form used for data collection (*left*) can be replaced by an observation form in a mobile app (*right*). Image by Whale mAPP © 2014. University of Redlands logo used with permission.

The app is geo-aware, providing users with species lists that are unique to their location (figure 8.5). This functionality is critical because species present in Southern California, for example, vary from those present in the Baltic Sea. Originally, regional species lists were provided to be entered manually, but a new script incorporates global distribution maps to automatically populate a list of probable species based on the user's location.

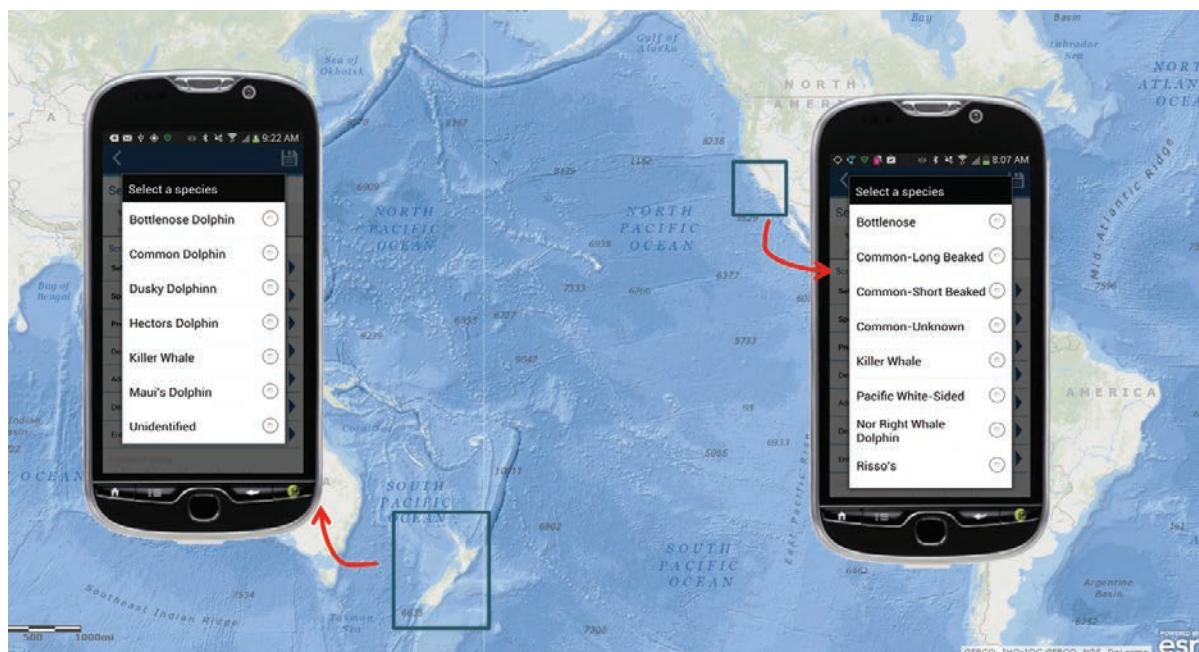


Figure 8.5. Whale mAPP's geo-specific species view ensures that users are presented with the most accurate list of species currently known in the region. Image by Whale mAPP © 2014. Data sources: Esri, GEBCO, NOAA, National Geographic Society, DeLorme, HERE, Geonames.org, and other contributors.

The My Data View of the app allows users to view basic information about their trip. All the data collected is currently stored in a SQLite database on the Android device itself. When connectivity is available, trips and observations can be either automatically or manually synced to ArcGIS feature services.

Web App

A web app has been developed to accompany the Android app, and it was designed with a branding technique that is similar to that of the Android app to provide users with a seamless experience. The animated home page provides basic information on the project and describes how to get started (figure 8.6). In addition to the home page, the site includes a learning component and map component.



Figure 8.6. The animated home page of the whalemapp.org website directs the user to additional information on the project and ways to get involved. Image by Whale mAPP © 2014.

The website's map allows users to visualize and query data. Datasets and corresponding photos are presented to the user on a map that is powered by feature services for both the track lines and observations (figure 8.7). Through the map interface, users can choose to view other contributors' observations or only their own. They can also query by species category and date range. A dashboard shows them how many track lines and observations are in their current query. The query capabilities and dashboard were designed to motivate users and provide them with the feeling of belonging to a community of fellow conservationists.

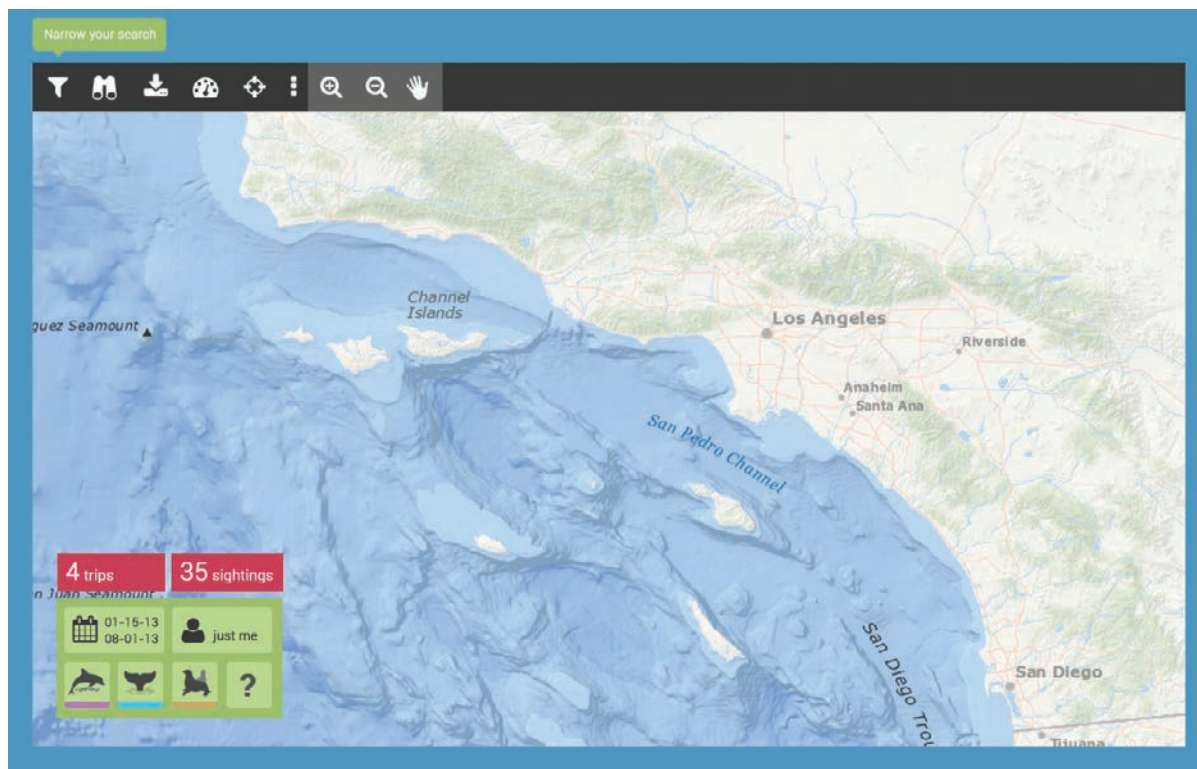


Figure 8.7. View of whalemapp.org’s map page includes map controls, querying and printing capabilities, and a dashboard. Image by Whale mAPP © 2014. Data sources: Esri, GEBCO, NOAA, National Geographic Society, DeLorme, HERE, Geonames.org, and other contributors.

Another goal of Whale mAPP is to empower users by giving them control of their data. Pop-up windows display observation details and allow users to correct previously recorded observation notes and upload associated photos. Photo upload is essential because photos are often taken with a device other than the phone, such as digital single-lens reflex (DSLR) cameras with zoom lenses. An additional feature of the website’s map is the capability to download data in shapefile format. This functionality is targeted at researchers, including those who make management decisions, but can also be used in educational settings.

The learning component of the website is meant to engage users in gaining a better understanding of species identification and conservation efforts and to provide educational material for use in the classroom. Species identification information is broken up by individual species and taxonomic group, using common names that are recognizable to a general audience (e.g., whales; dolphins and porpoises; seals, sea lions, and walruses).

Information for each general taxon includes descriptions of the biology of each group along with images to help users identify species that can be confused, such as true seals and sea lions. Details for individual species includes their common and scientific names, physical characteristics (e.g., length, weight, and coloration), prey, behavioral characteristics, distribution, social system/group size, predators, migration/dispersal patterns, population status, major threats, and “fun facts.” Each fact page includes photographs and illustrations (figure 8.8).

Identification


Whales ▶
Toothed whales
Baleen whales ▶
Dolphins & porpoises
Dolphins
Porpoises
Seals, sea lions, & walruses
Seals
Sea lions and fur seals
Walruses
Other carnivores
Polar bears
Sea otters
Dugongs & manatees
Manatees
Dugongs

Education

Conservation

Humpback whale

set region all



Scientific Name: Megaptera novaeangliae

Length: 13-14 m (43-46 ft)

Weight: 40,000 kg (44 tons)

Status: good to go

Prey: N/A

Physical characteristics

Black dorsal coloration and distinct hump. Unique tail with wavy trailing edges with black coloring on top and white underneath.

Behavioral characterization

Breaching

Distribution

All major oceans. In the North Pacific their summer range covers shelf waters from southern California to the Gulf of Alaska. Wintering grounds are off the coasts of Mexico and Central America, and around the Hawaiian Islands.

Population size

80,000 world-wide, 18,000-20,000 in North Pacific

Predators

Orcas and humans

Migration/Dispersal patterns

Migrate from their polar feeding grounds in the summer to tropical waters during the winter to give birth.

Social system/Group size

Live in loose knit groups in polar waters during the summer.

Major threats

Research efforts

N/A

Fun fact

Males engage in whale songs that can last up to 10-20 minutes but can be repeated for hours at a time. They have one of the longest mammalian migrations; can be up to 8,000 km (5,000 miles).

Figure 8.8. Draft view of the learning page of the whalemapp.org website showcasing species identification for humpback whales. Photo courtesy of Shane Keena Photography.

A major goal of the learning component of the website is to increase awareness of conservation issues that affect marine mammals. Threats such as pollution (solid waste, toxins, sound), human interactions (disturbance, entanglements, ship strikes), ecosystem shifts (global climate change, effects of overfishing), and disease are presented with descriptions, images, videos, and case studies. Research efforts are highlighted through the use of project descriptions and video clips of professionals in the field describing their research and emphasizing the importance of spatial data in their studies.

The learning component of the website also includes educational curricular materials focused on coastal marine mammal species to increase awareness and encourage conservation. GIS-based activities were developed to meet California state standards, specifically the Common Core standards and Next Generation Science standards (California Department of Education 2014a, 2014b). The materials use ArcGIS Online (arcgis.com), which is freely available to the public, so the only requirements are computers with Internet access. The goal of the educational materials is to help students gain experience in actually conducting scientific studies by generating hypotheses and analyzing data. Curricular activities help focus their questions on conservation themes to increase student awareness of threats to marine life and allow them to directly visualize these relationships. Video instructions and frequently asked questions (FAQs) are provided to help teachers get comfortable with the software and labs.

Baseline and Beta Testing

As previously mentioned, because of the variability in the expected user behaviors and skill levels, baseline and beta testing has become a critical component of the app's development. Baseline testing refers to a set of procedures that are performed on the app before its release to beta users. Each step in a procedure has an expected outcome that must be met for the test to be passed. There are baseline procedures for testing the setup menu; syncing functionality, region-specific offline basemaps, and species lists; and recording trips and observations.

Baseline testing helps eliminate errors and identify known issues. Whale mAPP's beta testers vary in geographic location, which impacts cellular and GPS dependability. Additionally, they vary in their intended use of the app. Some beta users are researchers on eight-hour trips to remote areas of the world, and others are average citizens on a two-hour whale-watching boat. These two different use cases present very different expectations of the app and reflect the range of target users. Beta testing has shed light on battery life and connectivity issues that have driven adaptations to the code base to make it more flexible for a wide range of users. For example, beta testing helped demonstrate the value in using a service to keep the app running in the background. When the app is minimized by the user, the track line is being recorded in the database without updating the map view on the screen. Additionally, when connectivity is lost, the underlying basemaps are paused until connectivity is regained. These options greatly reduce battery usage.

Additionally, beta testing has helped ensure that the accuracy of the locational data collected is comparable to the data collected scientifically. A beta tester in Dominica (Caribbean) ran the app side by side with a Suunto Ambit GPS watch and contributed trip data. The horizontal accuracy (~3 ft) of the Suunto watch provided a baseline for the accuracy needed for scientific data collection. The results of this testing (figure 8.9) demonstrate that the horizontal accuracy of the data collected using Whale mAPP is suitable for scientific-grade data collection. However, these results may vary in regions of the world with poor satellite reception.

Data Collection Comparison: Dominica

— Whale mAPP — GPS Watch

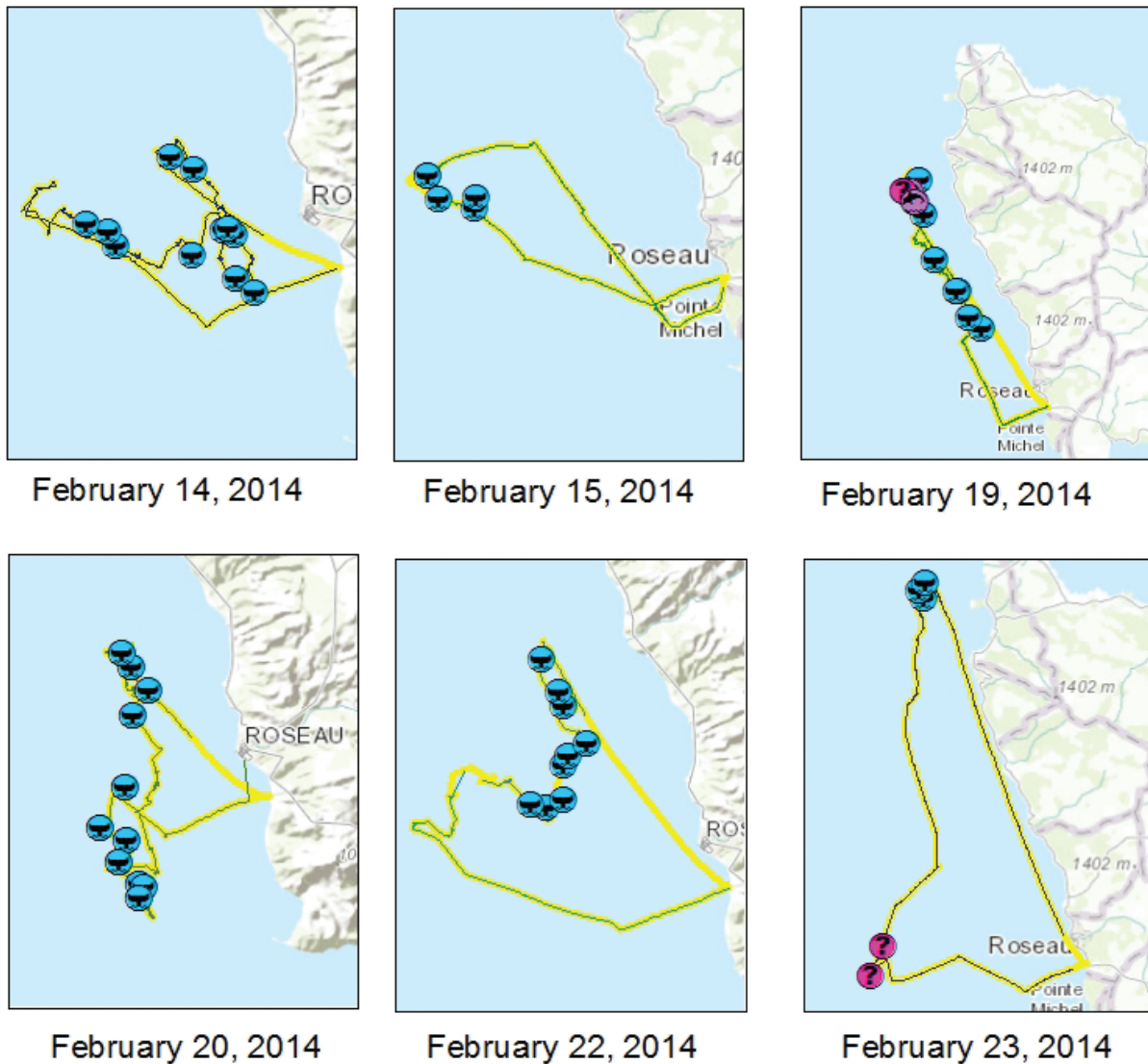


Figure 8.9. Data collected using Whale mAPP (purple) and a Suunto Ambit GPS watch (yellow) in Dominica (Caribbean). Suunto Ambit GPS watch data provided by Ted Cheeseman/Cheeseman's Ecology Safaris.

Image by Whale mAPP © 2014. Data sources: Ted Cheeseman/Ted Cheeseman's Ecology Safaris, Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, GIS User Community.

Additionally, beta testing has shed light on the stability of the mobile app. Because the app is not available in Google Play Store, it can be difficult to document crashes reported by users. Automated crash reporting for Android (ACRA)/Acralyzer is a light open source library used to send crash reports directly to the developer from the user's phone. This feature has helped identify stability issues with the app without imposing unrealistic demands on the user when or if the app crashes. Finally, beta testing has helped gauge the usability and scientific integrity of the data collected with the app. Beta testers have been key players in identifying errors in species-specific behavior lists and count options on the observation form. Additionally, they have helped identify and resolve unclear steps in the workflow for recording observations.

But Is the Data Good Enough for Science?

Data quality is of serious concern to members of the scientific community. Because of this need, several measures have been taken to ensure that Whale mAPP is collecting data of the highest quality possible. As previously mentioned, the observation data collection form in the Android app is based on a survey form used by an expert user and includes standard fields in marine mammal surveys. This structure ensures that the data collected includes essential information for scientific research.

Additionally, expert and public user accounts (figure 8.10) are both available when users register through the whalemapp.org website. Currently, experts are approved on a case-by-case basis and must provide justification for their credentials, such as an education in marine biology or certification as a whale watch naturalist. This key component makes the data useful for researchers because entries can be sorted by user type so that scientists may choose to include only expert submissions to increase their confidence in the accuracy of the data.

Figure 8.10 displays two screenshots of the registration form for the Whale mAPP, illustrating how the form dynamically changes based on whether the user is a public user or a subject matter expert.

View of registration form for expert users (left): This form includes fields for Full Name, Email Address, and Location Of Use. It features a selection for user type (Public User or Expert user) and a "Select best qualification:" section with radio buttons for Degree in marine biology (or related field), Boat captain, Naturalist on watch boat, and Other. An Additional Comments field is present at the bottom, along with a Submit button.

View of registration form for novice users (right): This form includes fields for Full Name, Email Address, and Location Of Use. It features a selection for user type (Public User or Expert user) and an Additional Comments field. A Submit button is located at the bottom.

Figure 8.10. The form used to register as a beta tester changes dynamically, depending on whether the user is a public user (*right*) or a subject matter expert (*left*). Image by Whale mAPP © 2014.

Additionally, options in the Android app's observation form are presented to users as drop-down lists, rather than as blank fields that require users to manually type or guess observation details, which ensures that all the necessary data is recorded. This option is particularly useful for fields on the observation form such as counts, behavior, weather, and sea conditions. It also reduces variability in the entry of information submitted. If a user attempts to save a submission before entering all the data, the user is alerted with a message to fill in the required fields. Using limited options also eliminates the dependency on user memorization, which is a key component of good user interface design (Norman 1988). User confidence in a sighting is self-reported via a five-star rating option so the user can indicate uncertainty, thus providing a researcher the opportunity to filter the data for the most accurate information.

The automatic tracking of each survey is one of the key features that make data obtained from Whale mAPP useful to scientific investigations. Survey lines provide scientists with information about the effort made in making marine mammal observations. To extrapolate from sightings data to any model of population distribution, information on both presence and absence of the target species is essential. Collecting appropriate data on effort, accomplished by both the survey tracks along with the confidence rating of data entered with each sighting, is helpful for differentiating variations related to effort versus variations related to true biological patterns and processes (Dickinson et al. 2010).

The last component for ensuring data quality is the use of the GPS chip on the phone. Using the GPS chip reduces the risk of error from transcribing locational information and also allows the app to automatically track surveys and observation locations. The quality of the GPS data can be controlled by the use of time and distance parameters for the location updates that are provided by the GPS provider on each device.

Comparison of Traditional Methods to Whale mAPP

To compare the ease, efficiency, and accuracy of the traditional data collection and mapping methods to Whale mAPP, researchers ran both protocols simultaneously for a trip off the coast of Catalina Island, California. Catalina Island is an excellent location for testing because of the island's unreliable cellular reception. The end product using both protocols was a map that shows track lines and observations symbolized by species type from the data collected.

Recording observations with the traditional survey form involves writing the time (from a watch), position (from GPS), and species information on a preprinted data sheet. All locations are stored as way points in the handheld GPS (Garmin GPSmap 62s), and the latitude and longitude are also written down as a backup. Tracks were stored by clearing the GPS at the start of each survey and saving the survey track at the end of each trip. In the field, both traditional and Whale mAPP methods required similar time commitments. In comparison, the traditional method requires two people, one to observe and read off the GPS information while the other records, whereas Whale mAPP requires only one user. The biggest difference in time investment is the additional time required to transform the collected data into a geospatial format. This procedure involves transcribing handwritten data into Microsoft Excel, uploading way points and track lines from the GPS, joining the data in GIS to produce the map, and symbolizing the sightings by species. Processing the data typically requires an experienced user at least one hour for a two- to three-hour survey, but the required time varies depending on the number of sightings and the GIS experience of the user.

The procedure for data collection using the Whale mAPP Android app has far fewer steps. Using the app, a trip is started from the home screen, and the track line is automatically recorded and displayed on a map view for the user as the trip is recorded. From the map view, an observation form is used to record the details for each sighting. Once the observation is saved, a point symbol is displayed on the map view that represents the species category being recorded. The app is designed to automatically sync the track lines and point observations to the Whale mAPP feature service. A *feature service* is an interface between an app and a GIS database that allows the transfer of user data to the database. Because the data is already stored in a geospatial format, the web app makes visualization of the data instantaneous. However, the same map created using the manual data collection method can be created in ArcGIS using symbols assigned for each species category to allow for additional analyses. The map (figure 8.11) displays data collected using Whale mAPP in comparison with that of Garmin GPSmap 62s (accuracy ~12 ft). This solution decreases the amount of time that researchers and volunteers spend in the field and can potentially increase the amount of data collected.

Data Collection Comparison: Catalina Island

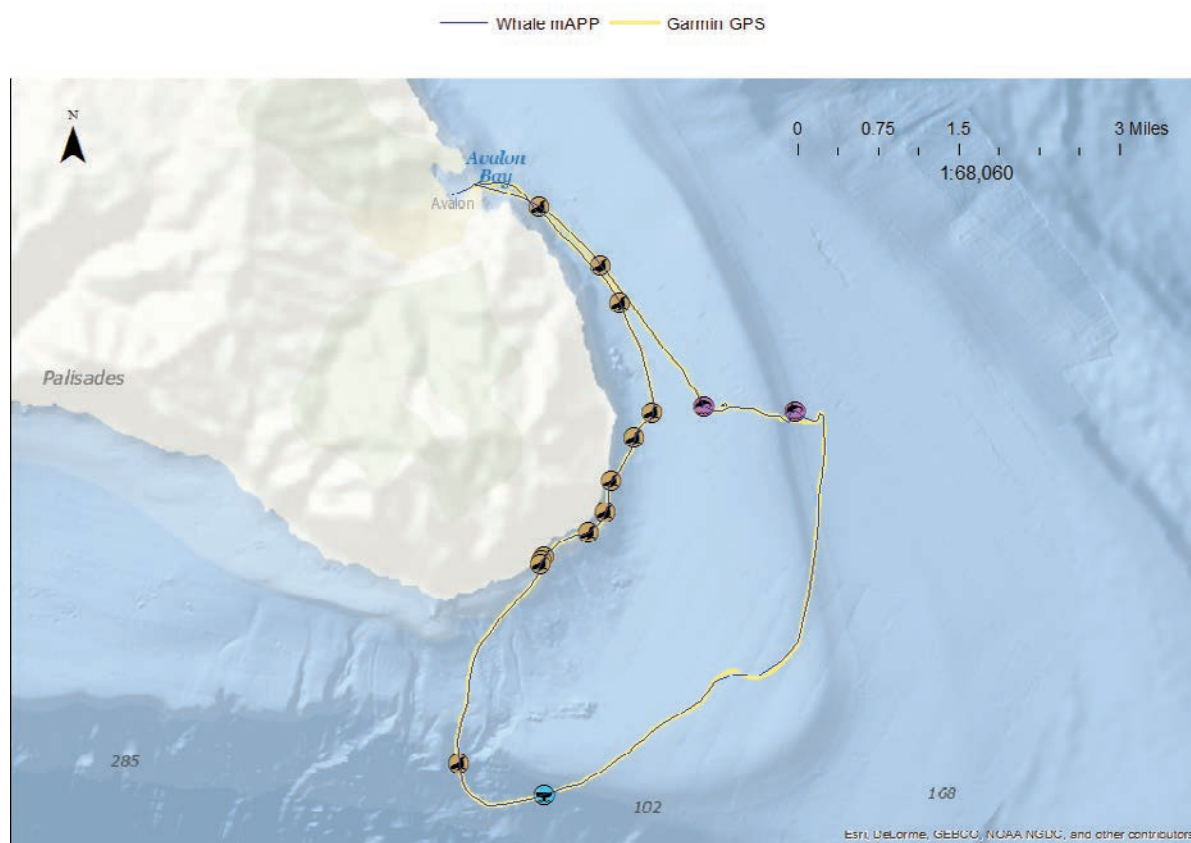


Figure 8.11. Comparison of track data collected using Whale mAPP and Garmin GPSmap 62s. Image by Whale mAPP © 2014. Data sources: Whale mAPP, Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors.

Ongoing Work

Several efforts are under way to expand the user base while Whale mAPP is still in beta testing. An important step will be to port the app from Android to the iOS platform to expand the potential user base to users with iOS devices.

Collaborative Coding, Collaborative Data Collection

Collaborative relationships are essential to ensure that data collected is easy for researchers to find, applicable to their research, and useful across a wide range of technologies. In addition to syncing data with the database at the University of Redlands, we are eager to extend Whale mAPP to allow users to share and export their data to a commonly used Microsoft Excel comma-separated value (CSV) format directly from their phones or to partner with organizations collecting similar types of data. Ongoing conversations with Whale Alert (targeted to a different audience) have led to agreements to help promote each other's data collection efforts (www.whalemapp.org/docs/partner-apps/) on each of our websites. We also plan to expand the photo-ID feature to foster collaborations with other research groups, including a project (<http://happywhale.com/about>) that encourages citizens to contribute photos of humpback whales to researchers in exchange for details on individual animals.

Collaborative Data Collection—Research on the Educational Benefits of Using Whale mAPP in Southeast Alaska

The Whale mAPP project collaborated with Courtney Hann, a graduate student at Oregon State University. Hann worked with the Geospatial Ecology of Marine Megafauna Lab, 501(c)(3) nonprofit Alaska Whale Foundation, coastal Alaskan communities, whale-watching groups, and environmental organizations to evaluate using Whale mAPP as a citizen science mobile app tool for monitoring marine mammals and improving marine mammal literacy in Southeast Alaska. For her research, Hann contributed educational components to the Whale mAPP Android app, including “fun marine mammal facts” that are displayed after each sighting is recorded. Additionally, Hann employed user surveys to assess the format of the mobile app and its effectiveness in educating participants about important marine mammal topics. Comparison of novice volunteer data to a standardized expert volunteer dataset is still under way. Through this collaboration, we will be able to explicitly test the primary hypothesis that Whale mAPP can educate citizen scientists while providing a low-cost approach for marine mammal monitoring.

From June to September 2014, 40 participants recorded 1,256 marine mammal sightings for this case study (figure 8.12). Data ranged from the northern portion of Southeast Alaska, near Glacier Bay, south to Seattle, Washington. Sightings included 664 humpback whales, 145 sea otters, 142 harbor seals, 116 Steller sea lions, 75 killer whales, 49 harbor porpoises, 42 Dall's porpoises, 12 Pacific white-sided dolphins, five California sea lions, two minke whales, two elephant seals, one fin whale, and one gray whale.

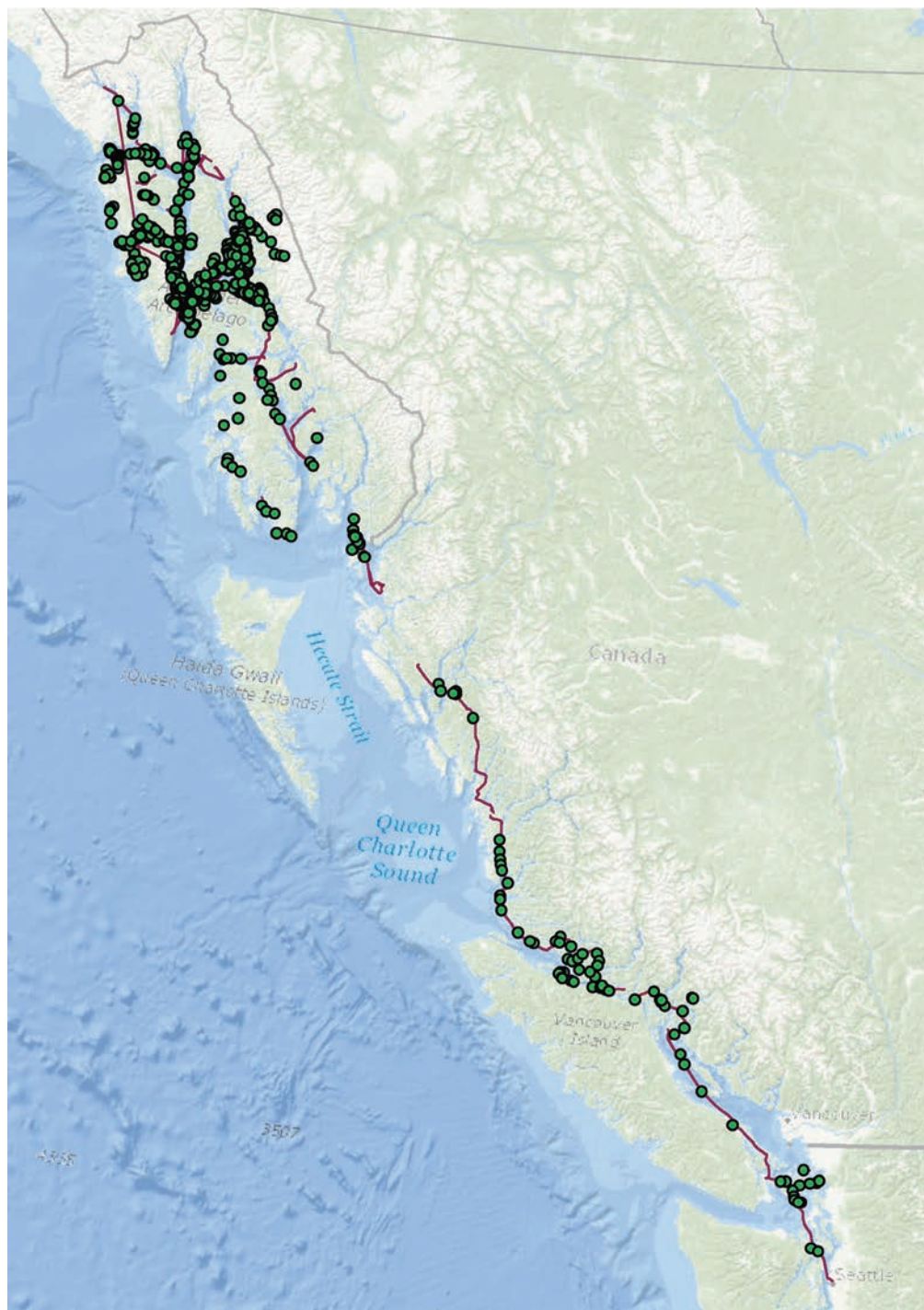


Figure 8.12. Map of the study area in Southeast Alaska and of the 1,256 marine mammal sightings recorded by 20 participants, June to September 2014. Image by Whale mAPP © 2014. Data sources: Whale mAPP, Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors.

Participants included guests and crew aboard commercial recreational charters, private-vessel operators, and commercial fishermen. All volunteers were provided with some type of training, either in-person if recruited at the Alaska Whale Foundation's Coastal Research and Education Center (CREC) or by PDF manual if recruited via e-mail. Furthermore, all users were provided with a marine mammal identification guide to assist in identifying marine mammals (figure 8.13). Training techniques, the user manual, and the marine mammal identification guide were designed to provide sufficient training and information for accurate data collection; all of which are important for citizen science projects (Bonney et al. 2009).

Volunteer participation varied, ranging from a week to several months of data collection. In addition to collecting marine mammal data, volunteers were asked to participate in two surveys, one distributed prior to using Whale mAPP and another two to four weeks after using Whale mAPP (permission to collect data on volunteers over age 18 was granted by the Oregon State University 5234 Institutional Review Board, study number 6273). As part of the first survey, a marine mammal identification test was used to rank the users; experts correctly identified more than 80% of the species, while those with lower scores were classified as novice users.

Evaluating Whale mAPP is important to recognizing educational and research accomplishments as well as highlighting areas of needed improvement. For instance, overall volunteer enjoyment of using Whale mAPP was exceptionally high; but data contribution was not equal among participants, as ~52% of the data was collected by two individuals. Understanding these details is important for improving Whale mAPP.

According to survey results, educational benefits from using Whale mAPP include specific content learning gains, a developing interest in science, and engagement in scientific practices. Results suggest participants improved their content knowledge of marine mammal identification skills but not of broader marine mammal conservation topics. Regardless, volunteers showed self-initiated learning potential by talking to a friend or scientist (57% and 35% of participants, respectively), reading a book (48% of participants), or looking up information on the Internet (43% of participants) to learn more about marine mammals. Results also suggest that Whale mAPP users were able to identify distribution patterns of marine mammals, highlighting a developing scientific practice of pattern recognition and distinction. These users were primarily motivated by a preexisting interest in and/or knowledge of marine mammals and secondarily by a desire to contribute to scientific research. Overall, results suggest that participation in Whale mAPP provides content learning in the form of species identification and pattern recognition and that users are actively pursuing more knowledge outside the program.

User experience and the format of the mobile app were also evaluated. A majority of participants enjoyed using Whale mAPP (~86%) and appreciated the added "fun marine mammal facts" (~71%) and marine mammal identification sheet (~71%). In addition, participants found the mobile app to be intuitive (~81%), and ~91% said they would recommend Whale mAPP to a friend. Around 50% of participants found different components of Whale mAPP easy to record, and ~20% enjoyed recording information. Conversely, ~17% found specific components excessive (particularly taking a photo of an animal), and ~11% were confused about how to record information such as the direction of a sighting and behavior of the animal.

The top two recommended revisions were to include more detailed behavior descriptions and switch to using a pin drop to mark animal locations. The first revision will be completed by Smallmelo Geographic Information Services, under the Mamie Markham Research Award (Hatfield Marine Science Center). The second revision requires more testing to evaluate the optimal method for novice users to record the animals' location in relation to their vessel.

Whale mAPP Marine Mammal Identification Guide – Baleen Whales

Humpback Whale (<i>Megaptera novaeangliae</i>) 	Gray Whale (<i>Eschrichtius robustus</i>) 	Sperm Whale (<i>Physeter macrocephalus</i>) 	Fin Whale (<i>Balaenoptera physalus</i>) 	Minke Whale (<i>Balaenoptera acutorostrata</i>) 
Most Common – most likely to be seen in inland waters	Rare – most likely to be seen in outside waters near Sitka	Rare – most likely to be seen in southern Chatham Strait	Rare – mainly near open water	Rare – mainly near Glacier Bay/Icy Strait
Size – medium (<45')	Size – medium (<40')	Size – medium/large (<60')	Size – large, occasional breach (<80')	Size – small, breach and aerial behavior (<30')
Fluke – present when diving	Fluke – present when diving	Fluke – present, triangular	Fluke – flukes when diving	Fluke – rarely seen
				
Dorsal fin – arched back	Dorsal fin – no dorsal fin	Dorsal fin – blunt, triangular	Dorsal fin – hooked	Dorsal fin – hooked
				
Blow – tall, bushy	Blow – moderate, bushy	Blow – tall, 45° angle	Blow – very tall, columnar	Blow – small, usually absent
				
Threats – gear entanglement, ship strikes, sonar and boat noise	Threats – collision with vessels, gear entanglement, habitat degradation, boat noise, disturbance from tourism	Threats – net entanglements, fisheries interactions (sperm whales have been recorded feeding off long-line gear)	Threats – oil/gas activities and increased shipping in higher latitudes	Threats – net entanglements, ship strikes, climate change effecting their prey distribution

Dall's Porpoise (<i>Phocoenoides dalli</i>) 	Killer Whale (<i>Orcinus orca</i>) 	Harbor Porpoise (<i>Phocoena phocoena</i>) 	Pacific White-sided Dolphin (<i>Lagenorhynchus obliquidens</i>) 
Most Common	Common	Occasional	Rare
Size – small (<7')	Size – large (<30')	Size – small (<6')	Size – small, sleek (<8')
Behavior – small groups, rooster's tail, often bow ride, no acrobatic tricks	Behavior – groups, several breaths followed by a long dive	Behavior – alone, quiet and elusive, can be difficult to spot	Behavior – groups, very social with frequent bow-riding and acrobatics
Dorsal fin – triangular, black & white	Dorsal fin – huge and black	Dorsal fin – triangular, all black	Dorsal fin – hooked, black and white
			
Acrobatic – no	Acrobatic – no	Acrobatic – no	Acrobatic – yes, leaps & flips
Threats – net and gear entanglement	Threats – net entanglement, long line fishing interactions	Threats – habitat loss, predation, disease, and pollution	Threats – habitat loss, predation, and disease

Harbor Seal (<i>Phoca vitulina</i>) 	Steller Sea Lion (<i>Eumetopias jubatus</i>) 	Sea Otter (<i>Enhydra lutris</i>) 	California Sea Lion (<i>Zalophus californianus</i>) 	Northern Fur Seal (<i>Callorhinus ursinus</i>) 
Common – near haul outs	Common	Common	Rare – outside waters	Rare
Size – small seal (<6')	Size – large (<8'(F) 10'(M))	Size – small sea otter (<5')	Size – medium (<6'(F) 8'(M))	Size – smaller sea lion (<6')
Behavior – shy, alone or in groups on ice, rocks, or beaches	Behavior – alone or on rocks in groups, very loud	Behavior – alone or floating in groups close to shore	Behavior – alone or in groups in the water	Behavior – alone, likely foraging for food
Water – short muzzle, will only see the head, near shore	Water – loud and active in groups, slap flippers	Water – floating on back, alone or in large 'rafts'	Water – loud and active in groups, slap flippers	Water – may see flippers
				
Land – quiet, on ice or rocks in sheltered shores, round, spotted	Land – loud groups on rocks or beaches	Land – quiet, elusive, rare on land	Land – on rocks or beaches, walk with flippers	Land – rarely on shore in Alaska
				
Threats – gear and net entanglements, pollution	Threats – competition for food, predation, and pollution	Threats – oil spills, disease	Threats – net entanglement, disease, predation	Threats – net entanglement, depletion of food, oil spills

Figure 8.13. Alaska specific marine mammal identification guide. Images by Whale mAPP © 2014.

Overall, this study suggests that Whale mAPP provides preliminary educational benefits to its users with the potential to improve as user feedback is implemented. As one ecotourism captain wrote, “I loved being able to use the app, and our passengers loved that I was sending information to you. It gives us and our guests a better sense of purpose and that the things we see might help you collect data.” Having a mobile app associated with the Whale mAPP program is advantageous as informal learning systems, including museums and science centers, are increasingly using technology to leverage their traditional techniques and engage more of their visitors (DiPaola and Akai 2006). This study supports Whale mAPP’s goal of providing a method to engage citizen scientists while providing educational benefit to users who are helping collect important marine mammal data.

Future work will evaluate the similarities and differences between expert and novice Whale mAPP data. The data will preliminarily be assessed on the basis of the difference between full datasets and reduced datasets. Reduced datasets contain only sightings that have a confidence rating of 4 or 5 (5 representing 100% confidence in data entered) and unlimited visibility. The results will reveal methods required to reduce user bias and error when evaluating Whale mAPP data. Second, the distribution of individual species will be examined. Considering the irregular boundaries and numerous islands in Southeast Alaska, a lattice-based approach of Barry and McIntyre (2011) will be used to generate estimates of 25%, 50%, and 95% total activity spaces for each species. Differences between expert and novice data in each activity space will be examined using a paired t-test in R, statistical significance at $P < 0.05$. The results will reveal whether the two datasets differ when predicting core-use areas (25% activity space) or larger area estimates (50% and 95% activity space). These additional explorations of the Whale mAPP data will decipher the usability of Whale mAPP data, the constraints needed to account for user and species bias, and potential research questions that can be answered using Whale mAPP data.

Conclusion

Marine mammal species face increasing threats globally because of a growing human population and the associated environmental degradation. Information on each species’ distribution and habitat use is essential to management efforts. Yet the vastness of the oceans and lack of funding make such data collection extremely challenging.

Whale mAPP provides an opportunity to capitalize both on the public’s fascination with these animals and the increasing number of people observing them in the wild. Mobile technology can greatly expand the cohort of interested citizens while increasing the accuracy of their data. The mobile app and associated website were carefully designed and tested to be user-friendly, engaging, and useful for recording and visualizing essential spatial data.

This global set of tools will continue to evolve with user feedback and collaboration in both the scientific and development communities. Whale mAPP has the capability to serve as a standard for baseline data collection while simultaneously encouraging users to actively contribute to scientific research and providing them with the education they need to act as stewards of marine life.

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CHAPTER 9^{Updated}

Extending Esri Geoportal Server to Meet the Needs of the West Coast Ocean Data Network and Inform Regional Ocean Management

Todd Hallenbeck, Steven J. Steinberg, Andy Lanier, and Tim Welch

Abstract

Lack of accessibility to geospatial data by coastal resource managers has been identified at the regional and national levels as a hurdle to improved ecosystem-based management in the United States. The West Coast Ocean Data Portal (<http://portal.westcoastoceans.org>) is a project of the West Coast Governors Alliance on Ocean Health to address this problem by working to increase discovery and connectivity of coastal and ocean data users and systems to better inform West Coast ocean health decisions. The West Coast Ocean Data Network is a community of practice connecting West Coast data managers and users to develop best practices for regional data sharing. Building on the West Coast Ocean Data Portal, we demonstrate how subsequent development of the data and tools can be used by resource managers to better assess the effectiveness of marine debris prevention policies on the composition and distribution of debris along West Coast beaches.

Introduction

The release of the US National Ocean Policy in April 2013 (National Ocean Council 2013) has ushered in an era of ecosystem-based management (EBM), which explicitly recognizes the need for spatial and temporal distribution of ocean resources and activities to minimize conflict between human and natural systems (Crowder et al. 2006; Young et al. 2007). As state governments work to address these issues, they join to form regional ocean partnerships that match the geographic extent of the ecosystems being managed (Hershman and Russell 2006). As these partnerships work to inform regional ocean health issues, challenges emerge relating to aggregating and accessing the best

available science and geospatial data at this regional scale (WCGA 2006; Hennessey 2011; Obama 2013). Marine debris prevention is one such issue that has received regional attention because of its negative effects on vulnerable coastal habitats, marine life, and recreational quality.

The West Coast Ocean Data Portal (WCODP) (WCGA 2014) is a project of the West Coast Governors Alliance on Ocean Health (WCGA) designed to address data access and aggregation issues by working to improve discovery and connectivity of coastal and ocean data and people. The WCODP is working to better inform West Coast ocean resource management, policy development, and planning. The WCODP is a web app built on Esri Geoportal Server open source software (Esri 2014) and integrated with a map-viewing app to selectively harvest, curate, and visualize data resources from the West Coast Ocean Data Network (WCODN). Additionally, the WCODP recently incorporated tools and data to inform marine debris decision-making related to cleanup planning and prevention policies.

The West Coast Ocean Data Network

The WCODN began in 2012 as a grassroots group of data managers and users from state and federal agencies, tribal governments, nongovernmental organizations (NGOs), and universities. Members of the WCODN are dedicated to sharing best practices that are appropriate to increasing the accessibility of West Coast ocean and coastal data for regional ocean management, policy development, and planning. The WCODN is organized into three working groups: data, information technology, and outreach (figure 9.1). WCODN members contribute to and guide the development of the WCODP, share lessons learned from their respective data management efforts, and respond to requests for regional data.

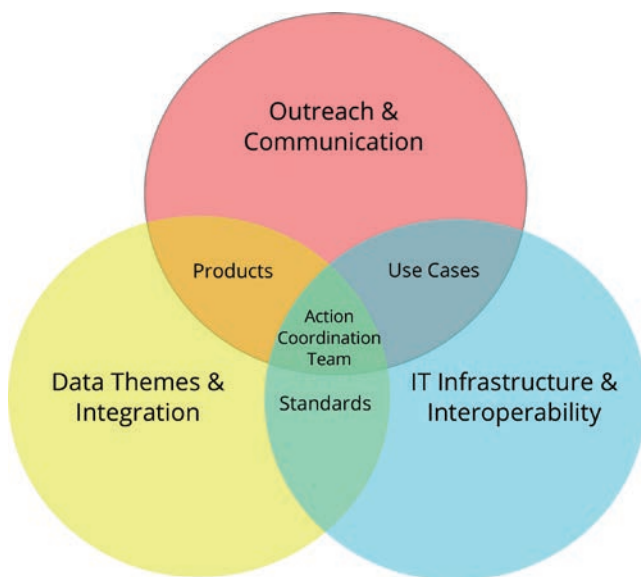


Figure 9.1. West Coast Ocean Data Network structure and function. Three working groups, data, information technology, and outreach, support the development of the West Coast Ocean Data Portal and develop and share data best practices.

The underlying design strategy of the WCODP is to avoid duplication of existing efforts of WCODN members in the region. The WCODP connects data catalogs maintained by members of WCODN and selectively harvests and curates the best available data resources from each contributor

(figure 9.2). These datasets are then published through a modern, lightweight portal that is designed to meet the expressed needs of the WCGA for data organization and discovery. The actual datasets are not harvested by the WCODP. Instead, standardized metadata is harvested, which contains service links to access the data in all its various forms, whether it is a file or web service. The benefit of this approach is that the dataset resides with the original provider, who is able to control what is published, and WCODN ensures that members can communicate their changes. Having access to a more comprehensive set of data resources is the primary reason behind marine debris experts expressing a desire to interact with the WCODP.

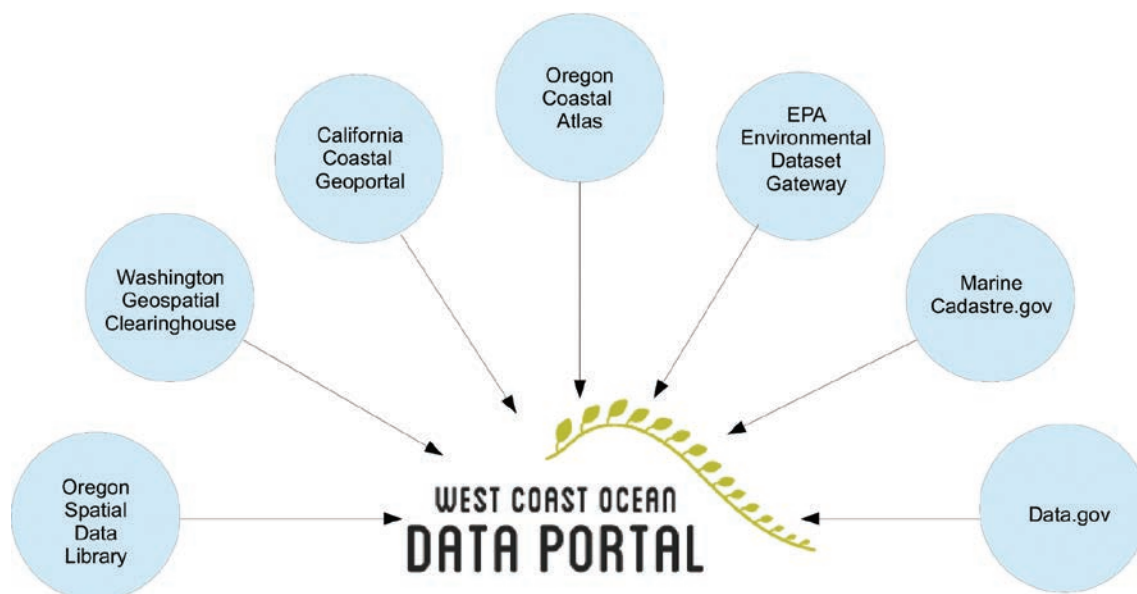


Figure 9.2. Diagram of diverse West Coast Ocean Data Network partner catalogs.

Members of WCODN contribute data to WCODP because they see value in collaborating with regional partners to advance their agency, organization, or tribal mission or mandates for coastal management. WCODN members also benefit from wider advertisement and accessibility of data holdings to new user groups and stakeholders, technical capacity building through WCODN working groups and training, demonstration of the regional collaboration and sharing often required by grant funding agencies, and inclusion of data in decision-making for regional issues such as sea-level rise adaptation, ocean acidification, and marine planning.

The challenge to this networked approach is that WCODN members are both geographically and technologically diverse with respect to their individual data-sharing infrastructure and practices. For example, WCODN members currently use at least seven different data catalog products, including

- Esri Geoportal Server,
- Comprehensive Knowledge Archive Network (CKAN) (The Open Knowledge Foundation 2014),
- GeoNetwork,
- pycsw (Karlidis et al. 2014),
- Thematic Real-Time Environmental Distributed Data Services (THREDDS) Data Server (Unidata Program Center 2014),
- Mercury (Oak Ridge National Laboratory 2013), and
- ArcGIS Online service (arcgis.com).

Within these catalogs, data resources are represented by at least four different metadata standards, including Dublin Core, Federal Geospatial Data Committee (FGDC), Content Standard for Digital Geospatial Metadata (CSDGM), International Organization for Standardization (ISO) 19115, and ISO 19115-2. In order to succeed, the WCODP had to accommodate the diversity of technology and standards used by WCODN partners to fulfill the diverse data requirements from the marine debris community.

Data Catalog Requirements and Testing

In late 2012, four different data catalog products were thoroughly assessed and considered for the West Coast Ocean Data Portal, including Esri Geoportal Server, GeoNetwork, CKAN, and pycsw (Welch et al. 2012). The primary requirements assessed included that the product

- possesses an open source license, is well documented, and is supported by a responsive development team;
- provides a full-featured application programming interface (API) allowing the catalog to be readily integrated into a larger portal solution with its own distinct user interface (UI);
- provides faceted search capability, allowing users to drill down or filter their search by theme, geographic area, source, service type, or other characteristics;
- supports selective metadata harvesting from data catalogs, using the standard Catalog Services for the Web (CSW), as well as CSW server capabilities so that others can harvest WCODP itself;
- supports alternative or nonstandard metadata harvesting when needed (e.g., from web-accessible folders [WAF], THREDDS, and ArcGIS Online);
- supports a variety of metadata standards, including ISO 19115, ISO 19115-2, FGDC CSDGM, and Dublin Core; and
- allows metadata records to be curated by organizing into one or more groups, effectively supporting the creation of a simple taxonomy for West Coast-specific categories and issues.

As of January 2013, testing showed that only two data catalog products met the majority of our requirements. Esri Geoportal Server supported all the metadata standards but not faceted search. By contrast, CKAN supported faceted search but lacked full CSW capabilities and did not support the required metadata standards. After conversations with both development teams, we determined that CKAN was in the process of covering some of the identified feature gaps through enhancements being developed for the Data.gov platform. However, it would not be ready in time for this project. The Esri Geoportal team demonstrated that they were working on support for faceted search and would be able to provide early access to those enhancements to our team. Esri Geoportal Server was selected as the WCODP data catalog solution, and over the months to follow, the WCODP team and Point 97 (2014), an ocean technology solution company in Portland, Oregon, worked closely with the Esri Geoportal development team to help shape and test these enhancements.

West Coast Ocean Data Portal Architecture

In July 2013, Point 97 released a beta version of WCODP that incorporated Esri Geoportal Server with a PostgreSQL back end, leveraging a newly released Geoportal functionality called the Geoportal Facets Customization (GFC) (figure 9.3). The GFC component pulls metadata documents from the backend Esri Geoportal Server database and passes them through to Apache Solr (The

Apache Software Foundation 2012), a search platform that provides full-text, faceted, and geospatial search capabilities, which are accessible through a robust API. The WCODP UI uses this Solr API to provide users with the ability to rapidly search and filter through the available datasets by keyword, category, location, or source (figure 9.4a). Discovery of resources through faceted search is often used in modern e-commerce websites, allowing visitors to quickly drill down and find their product of interest. In the case of WCODP, instead of filtering by product price and feature, the GFC component creates search facets that are tuned for discovery of spatial datasets. Once a user finds a dataset of interest, the user is provided with a range of additional information through the metadata, including the title, abstract, date published, creator, publisher, contact, use constraints, and all the available links for accessing the resource (figure 9.4b).

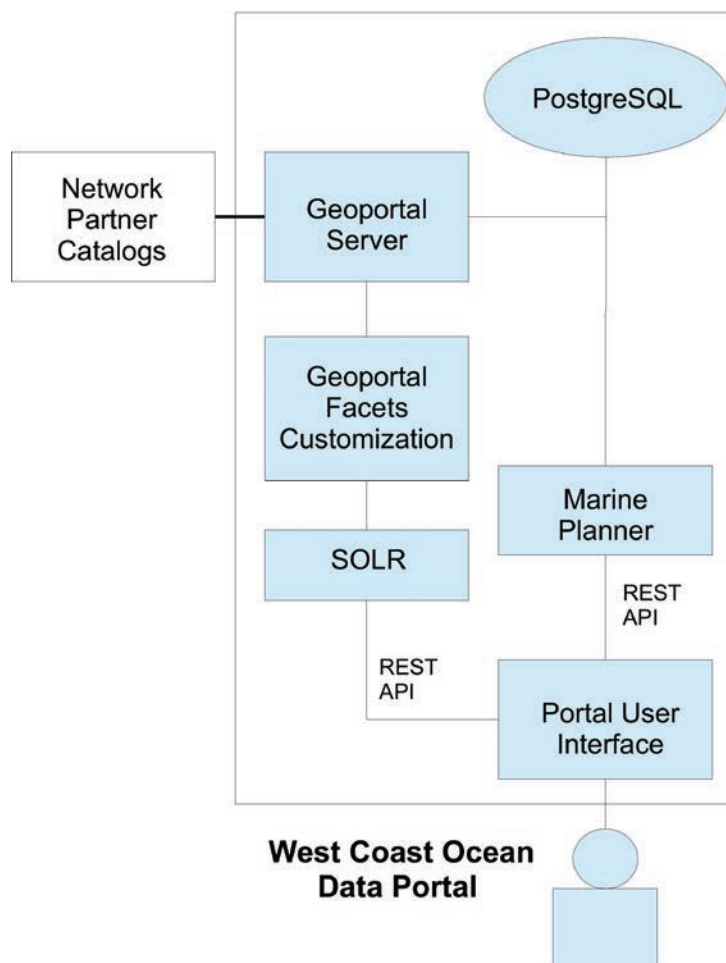
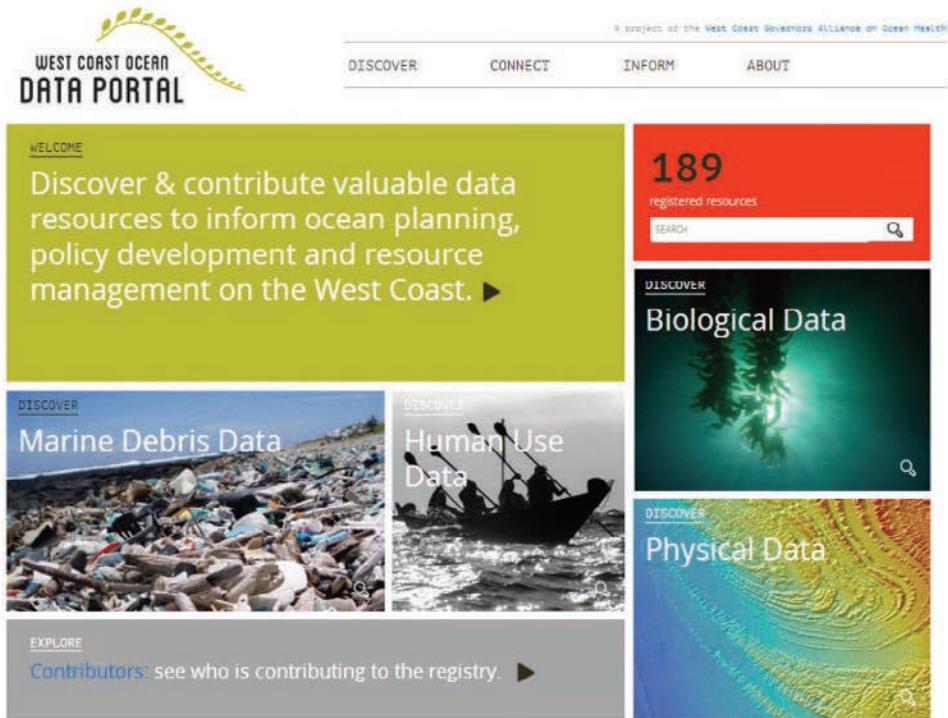


Figure 9.3. Diagram of West Coast Ocean Data Portal system architecture. Network partners contribute metadata in standards-based XML documents to Esri Geoportal Server. The Geoportal Facets Customization pulls discovery metadata fields from the Geoportal and pushes them into Apache Solr, which provides a robust, faceted search API that drives the portal user interface.

a



b

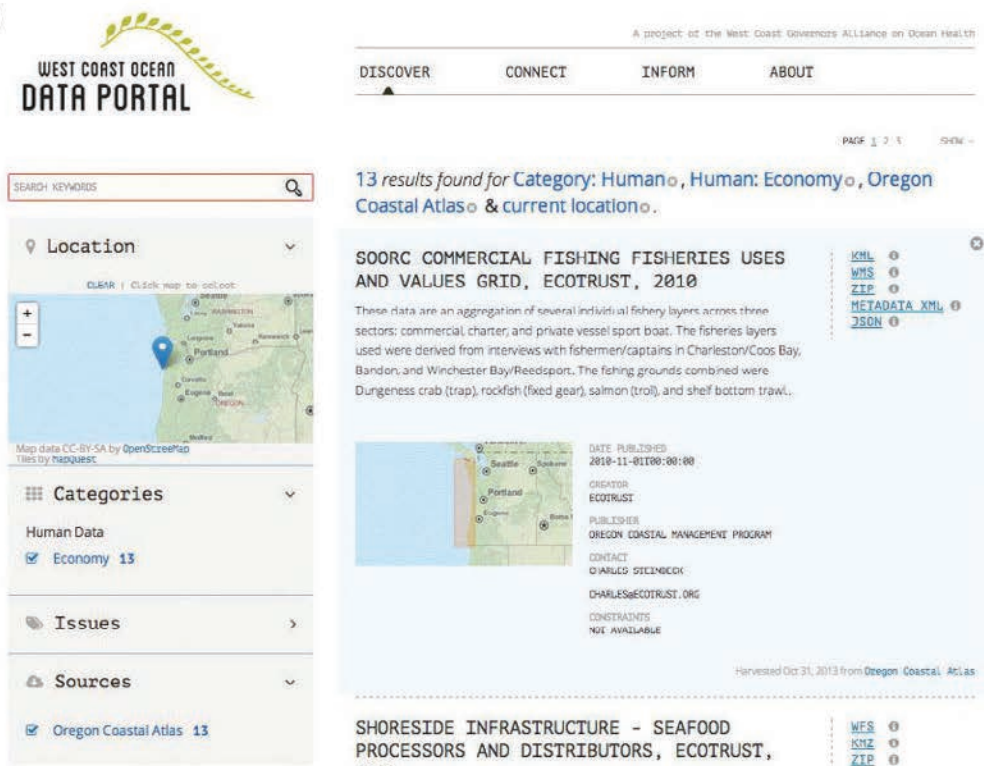


Figure 9.4. The (a) custom home page and (b) search interface of the West Coast Ocean Data Portal. The search interface allows users to drill down and discover datasets using a variety of search facets, including location, category, issue, and source. Images courtesy of the West Coast Governors Alliance; location map data CC-by-SA by OpenStreetMap; titles by MapQuest; “SOORC Commercial Fishing Fisheries Uses and Values Grid, Ecotrust, 2010” courtesy of Oregon Coastal Management Program, harvested October 31, 2013, from Oregon Coastal Atlas.

This detailed information, in many cases, is queried directly from Esri Geoportal Server, using its provided representational state transfer (REST) API rather than Solr. The strategy, in this case, is not to push everything through Solr but to provide it with only the metadata fields needed for search and discovery of datasets and their service links. More detailed metadata can then be queried directly from Esri Geoportal Server. Point 97 developed an attractive, custom front end to consume the Geoportal's REST and Solr JavaScript Object Notation (JSON) APIs. This API-driven approach allows a variety of software components, which each do a separate job, to be integrated into a unified website through a customizable user experience.

In January 2014, the WCODP was formally released to the public with an initial catalog of over 180 data resources for the West Coast contributed by seven network partners, including state and federal agencies. The strategy is quality over quantity, and the catalog has continued to expand as new data resources come online and additional network partners are connected. Over 780 data resources contributed by 25 network partners have been made available.

Prioritizing Portal Expansion for Marine Debris

Early in 2013, the WCGA formally recognized marine debris as one of the highest-priority issues for the West Coast region. Agencies and organizations have mobilized around the issue of marine debris for decades through both cleanup and prevention strategies. The WCGA recognized that there was a lack of data at the West Coast scale that could answer questions such as where debris was occurring, where it was coming from, how much debris there was, what type of debris it was (plastic, metal, wood), and whether it was changing over time—information that proved essential for these groups to better target their efforts and measure their effectiveness.

Plans were already under way to expand the WCODP with data visualization and map-viewing capabilities in 2014. The decision was made to focus these efforts on the marine debris issue, organize the information needed, and synthesize it into a form that could be readily used by cleanup coordinators, state regulators, and policy advocates. The goal was to expand the data portal in a general-purpose or repeatable manner so that it could scale to support the other priority issues of the region, such as sea-level rise and ocean acidification. In November 2013, this work began by convening experts working in all areas of marine debris to look at how the WCODP and the resources it harvests could support them in their work. The discussion revolved around two particular debris-related data resources. First is the West Coast Marine Debris Database (WCGA 2012), which aggregates beach cleanup and derelict fishing gear removal data from organizations working up and down the West Coast (figure 9.5). The WCGA Marine Debris Action Coordination Team and Point 97 developed the database. The second resource is the National Oceanic and Atmospheric Administration (NOAA) Marine Debris Monitoring and Assessment Project (NOAA 2013), an initiative to collect baseline data on the amount and type of debris in the environment from an increasing number of sites up and down the West Coast.

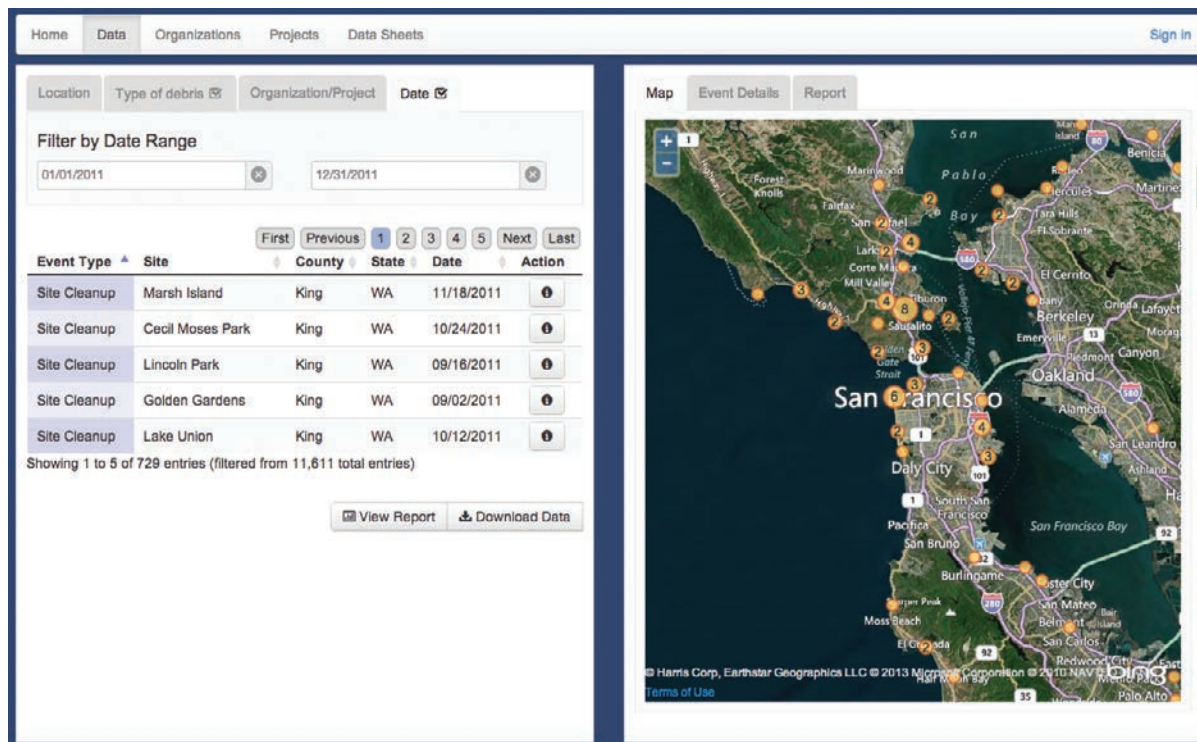


Figure 9.5. West Coast Marine Debris Database event search and reporting page. This website provides access to beach cleanup and derelict fishing gear event data. The West Coast Ocean Data Portal plans to visualize web services from this database, along with services from other datasets in the portal, to inform the issue of marine debris preventions and cleanup on the West Coast. Courtesy of West Coast Governors Alliance on Ocean Health.

We started the process by integrating the West Coast Marine Debris Database API with the WCODP and summarizing the information it contains in more useful ways, including visualizing it on a map. One example is the aggregation of derelict gear removal events from the site level to larger geographic units and symbolizing them on the basis of frequency of removal (figure 9.6).

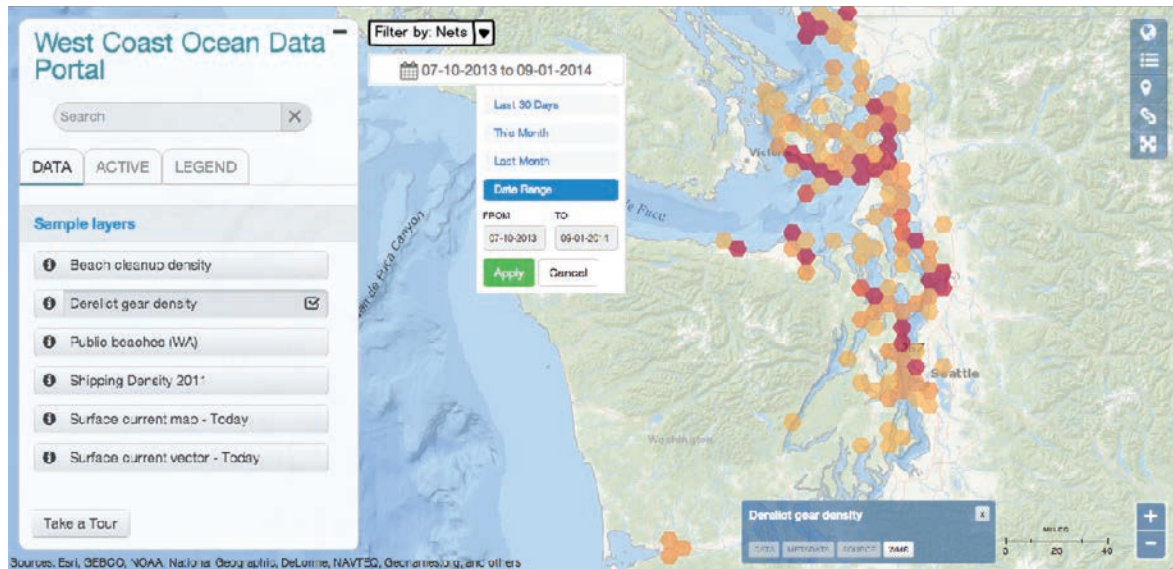


Figure 9.6. Design wireframe of the West Coast Ocean Data Portal map viewer using Marine Planner technology. Shown with derelict gear data layer with real-time filtering by category and time. Hexagons represent the number of fishing nets found at a particular location during the specific time period. The red to yellow color ramp reflects the high to low number of nets found. Courtesy of West Coast Ocean Data Portal; data courtesy of Esri, GEBCO, NOAA, National Geographic Society, DeLorme, NAVTEQ, Geonames, and others.

Rather than representing a snapshot of the data, this map view can be created in real time by querying the most recent data from the West Coast Marine Debris Database, using its REST API. Furthermore, users can select a specific time range of interest, as well as the specific type of debris they want to see, and the map view can be updated in real time to show that specific subset of data. Other data layers that pertain to source and sensitive habitats can be added to the map, using web mapping services hosted and published through partner organizations. This functionality is built into the WCODP using Marine Planner (see figure 9.6), a platform that was developed by Point 97 in partnership with The Nature Conservancy to provide robust map visualization capabilities as well as a wide variety of scenario and sketch planning tools (figure 9.7).

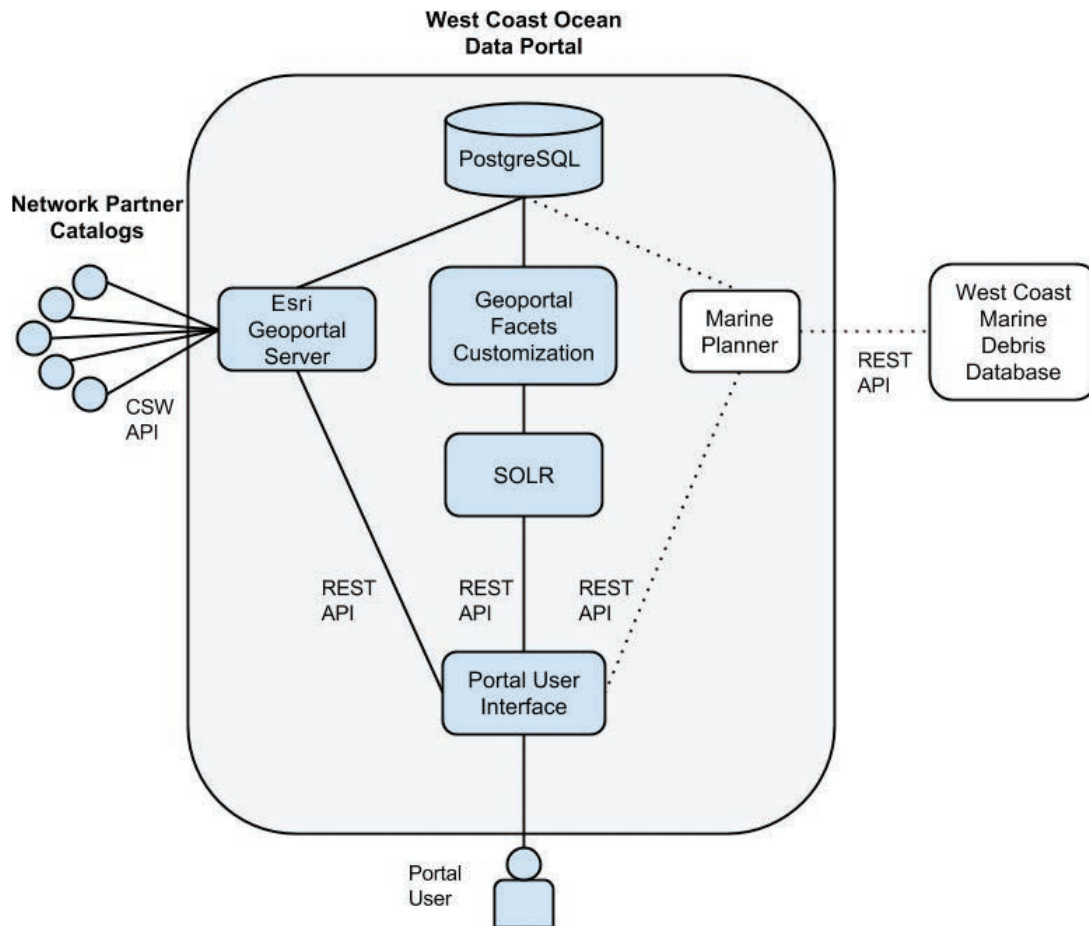


Figure 9.7. Diagram of West Coast Ocean Data Portal system architecture. Network partners contribute metadata in standards-based XML documents to Esri Geoportal Server. The Geoportal Facets Customization parses metadata from Esri Geoportal Server and passes it through to the ocean data portal user interface. The user interface also provides users access to the Marine Planner data visualization tool.

The latest version of the WCODP was released with the new map viewer and marine debris datasets in mid-2014, complemented by a variety of new datasets and map layers, including

- beach access points,
- boat launches,
- population centers,
- river and sewer outfalls,
- sensitive marine areas,
- watershed boundaries,
- biological inventories,
- nearshore habitat characteristics (shore zone),
- oceanographic data (wind, surface currents), and
- essential fish habitat.

The Marine Planner technology allow users to quickly create map views, print them, and share them. Taken together, these new data and tools provide the marine debris community with the resources needed to address some of its most pressing resource management questions.

Assessing Marine Debris Prevention Policies with the WCODP: An Example from Los Angeles County, California

Marine debris is a problem that costs West Coast states and communities millions of dollars each year in cleanups and ecosystem impacts (Stickel et al. 2012). In the face of this problem, local and state jurisdictions have enacted and implemented a variety of debris prevention policies to combat debris entering coastal waterways. Bans of single-use plastic bags and polystyrene foam food containers are some of the best-known examples of such policies. Despite the proactive nature of these prevention policies, little is known about their effectiveness in reducing either the concentration or composition of debris observed on beaches and waterways. External factors such as policy compliance, storm drain retention efforts, stream flows, ocean surface current conditions, and debris contributions from adjacent jurisdictions can all affect whether the debris ends up on a particular beach (Coe and Rogers 2012).

The WCODP features data and tools to help assess these factors and understand how baseline debris compositions change over time. Using the best available data from the Marine Debris Database, the WCODP allows users to filter beach cleanup information by debris type and time period to conduct before and after analysis on how debris composition changes with the addition of prevention policies. Additionally, users can view data layers that represent spatial depictions of prevention policies, rivers and streams, ocean currents, and population densities to provide context for the cleanup data.

As an example of this analysis using the data and tools provided by the WCODP, we visited Southern California. Los Angeles County banned foam containers from public facilities in January 2011. We compared the number of foam containers found on Los Angeles County beaches for the four years before and after the ban went in effect, by using WCODP filtering tools to select debris data by temporal period (Jan. 1, 2007, to Jan. 1, 2011, and Jan. 1, 2011, to Jan. 1, 2015) and foam container debris type. Although individual sites changed by varying degrees (table 9.1), the average across all sites reveals a nearly 40% reduction in the number of foam containers found on area beaches, as reported to the West Coast Marine Debris Database (figure 9.8). Debris database practitioners can create and share these maps to justify and advocate for similar prevention policies elsewhere along the coast. Additionally, the analysis reveals that although there were overall observable reductions in the amounts of debris in LA County, specific sites (e.g., Santa Monica) experienced an increase in the amount of foam containers during the same time period. Whether this increase is from upstream sources outside the jurisdiction of the container ban, local increases in use from nonpublic facilities, or even uncertainty in the data collection, this data provides resource managers with evidence of policy effectiveness while also suggesting that it may take policy improvements to achieve desired outcomes. These changes can include expansion of the ban to all facilities, adoption of measures at the state level, and better data collection and monitoring of sites.

Table 9.1. Comparison of Individual Beach Cleanup Sites before and after Foam Container Ban

Location	Debris Before	Debris After	% Change
Leo Carrillo	23	—	—
Zuma	921	262	−72%
Malibu	63	60	−5%
Santa Monica	2614	2855	+8%
Dockweiler	3876	1169	−70%
Redondo	282	234	−17%
Cabrillo	215	191	−11%

Note: The numbers indicate the number of foam containers on the beach.

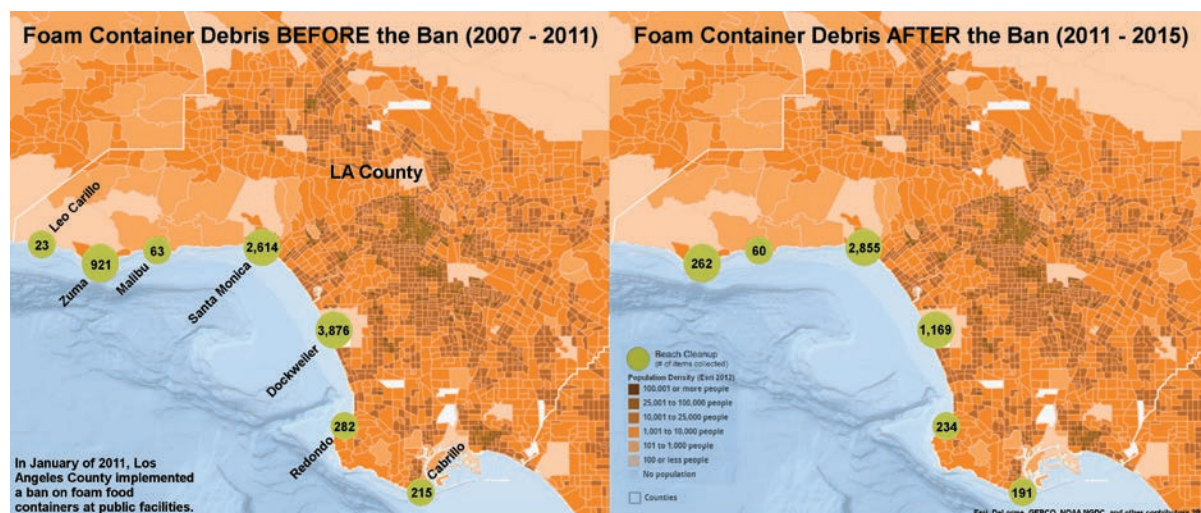


Figure 9.8. Los Angeles County banned foam containers from public facilities in January 2011. The maps compare the number of foam containers found on Los Angeles County beaches for the four years before and after the ban went into effect (January 1, 2007, to January 1, 2011, and January 1, 2011, to January 1, 2015). The comparison reveals a nearly 40% reduction in the number of foam containers found on area beaches, as reported to the West Coast Marine Debris Database. Courtesy of West Coast Ocean Data Portal. Data sources: Esri, GEBCO, NOAA, National Geographic Society, De Lorme, HERE, Geonames.org, and other contributors.

The beach cleanup data contained within the WCODP and Marine Debris Database represents much of the best available data for conducting this type of analysis on the West Coast; however, this type of citizen-collected and reported data has clear limitations. This data is collected on an opportunistic basis, with no defined method to standardize the level of effort and protocols used at any given cleanup event. This randomness confounds subsequent data interpretation because the number of items found could be directly related to the number of cleanup events, volunteer turnout, or success of data upload to the Marine Debris Database within a given time period. Similarly, there are no standardized methods for collecting beach cleanup data among the 15 cleanup groups that currently provide data. Therefore, some cleanup activities that lack counts of items or specific locations cannot easily be included in the debris database. Although these factors are real and affect the certainty of any analytical approach, we view the WCODP as a planning tool that highlights areas for further analysis using more powerful tools and additional datasets. Another benefit of this exercise is that it has prompted efforts within the marine debris community to work toward

standardizing methods, terminology, and reporting mechanisms to improve the comparability of data across the West Coast region.

Relevance to Ecosystem-Based Management and Regional Decision-Making

Lack of accessibility to geospatial data has been identified at the state, regional, and national levels as a hurdle to improved EBM in the United States (WCGA 2006; Hennessey 2011; Obama 2013). For regional EBM, data needs are cross-disciplinary and cross-jurisdictional, compounding the challenge to acquire and use data in public policy processes. The need to aggregate data from multiple agencies and subject domains places a high premium on the development of frameworks that bring together geodata from multiple sources in an easy-to-use portal. Technologies that take advantage of standards-based metadata formats and web services allow for a distributed network of data providers to contribute to common systems that can better inform regional decision-making.

However, despite availability of required technological infrastructure to support distributed sharing, the success of these systems relies on a strong network of partners to develop, adopt, and promote common standards. Fostering communication within and between members of the network is essential to maintaining a strong foundation and accountability for contribution of data. Furthermore, it is imperative to formalize relationships between partners in the network to ensure coordination and foster communication mechanisms. Without human networks such as the WCODN, the success of distributed and dispersed data sharing is not possible.

The development of the WCODP is an important first phase in development of a regional system for cataloging data, connecting people, and informing ocean issues through web mapping apps. These systems are increasingly being developed and used across the country as marine spatial planning and EBM take place at regional scales. Within regions including the Northeast, mid-Atlantic, and Caribbean, regional planning bodies are forming to tackle the issue of marine spatial planning. These policy-making bodies are relying on quick and intuitive information delivery systems to understand the conflicts and opportunities in their ocean space. Web-based apps such as WCODP provide a source of authoritative science and make it transparent and accessible to policy makers and stakeholders alike.

The WCGA has identified regional ocean priorities focused on marine debris, sea-level rise, and ocean acidification. The WCODP continues to develop data and visualization tools focused on these issues to inform coastal managers, decision-makers, planners, and stakeholders to facilitate data and visualization tools about the trends and impacts of these issues on coastal ecosystems and communities. The WCODN will continue to act as a forum for the discussion and coordination of data-related issues to facilitate the growing interoperability and function of systems and data on the West Coast.

Best Practices for Regional Data Sharing

The WCODP demonstrates how metadata, combined with web technologies, is changing the way we discover and use geospatial data for regional ocean management. Traditionally, metadata has been used to document the methods and protocols behind a particular dataset (Qin et al. 2012). Although that role is essential in providing user context and the certainty necessary to select and use a dataset

properly, metadata is now an important driver in the discovery process. Additionally, as web services become the norm for data sharing and web apps, metadata that is packaged with web address links for direct download, web services, and other formats is increasingly being used to advertise agency, institutional, and tribal data assets (Tsou 2002). Because these technologies still rely on the quality of the underlying metadata, the challenge for data providers is to adapt their metadata practices to serve both objectives: ensuring that their data (1) is properly documented and (2) can be readily indexed by catalog systems to facilitate its discovery.

A growing shift has occurred over the last decade from metadata repositories being used as static text documents to new, dynamic pathways for data access, discovery, and use (Nopgueras-Iso et al. 2005). This shift is important because it reinforces the need for high-quality metadata and highlights standards such as ISO 19115-2 as being critical to documentation of data in multiple formats within one metadata record. In the past, metadata was an afterthought, but with the rise of metadata catalogs such as the California Coastal Atlas, Data.gov, and the WCODP, metadata records have become the face of data and sometimes are the first data component seen. UI design that styles the metadata and leverages the information it contains to offer discovery features such as facets, temporal search, and constraining by geography is important in connecting users seamlessly to data through the metadata.

The distributed framework for sharing through the WCODP required the adoption and promotion of data-sharing best practices to ensure that partner data catalogs are interoperable with the data portal. The WCODN data and information technology working groups started developing practices and policies related to registering data in the portal; development of metadata, web services, and catalogs; and the implementation of open data policies within partner organizations. Part of this effort was also developing criteria for inclusion of data in the portal. For example, the data must be documented in an FGDC or ISO metadata standard format, be state or regional in scale, and meet one or more priority needs of WCGA. It is recommended that the record be accessible through a standards-compliant, CSW-enabled catalog; provide links to web services (both Open Geographic Consortium and vendor-specific) or direct download; and make use of existing keywords from established taxonomies. On this last point, the WCODN has promoted the use of ISO keywords as well as building and publishing a West Coast taxonomy that can be included in metadata records to facilitate easy search and discovery. Additional best practices are aimed at reducing redundancy and confusion around published records by encouraging data providers to publish only data that they develop and maintain. This helps reduce uncertainty about the “freshness” and authoritativeness of data. The WCODP does not republish records to other catalogs unless the data is originally developed by the WCGA. Development of best practices helps promote interoperability and widespread data sharing, which has implications not only for how data is discovered, but also how datasets are used in regional ocean ecosystem management.

Conclusion

The WCODP is already providing benefits to the discovery and connectivity of coastal and ocean data and people, particularly in the realm of marine debris policy and prevention. This network of information and expertise better informs West Coast ocean resource management, policy development, and planning. The WCODP team successfully customized an instance of Esri Geoportal Server to harvest, curate, and publish geospatial resources from a diverse set of WCODN partner catalogs and information nodes. By building on Geoportal’s powerful back end to harvest and publish diverse metadata resources, the front end was customized with a visually appealing and

intuitive UI to enhance data discovery. Rather than aggregating data in a single portal location, the WCGA chose a federated data portal approach as a model for developing an effective, decentralized regional data portal. A primary advantage is that data and its associated metadata remain close to the authoritative source, which helps ensure that the data is maintained by the entities that are directly responsible for its creation and upkeep. This decentralized approach has successfully informed aspects of regional ocean management related to marine debris prevention. The demonstration of this approach to this regional ocean health issue is an example of how the data, tools, and network can be used to inform decision-making. As the WCODP continues to work with this resource management community, the analytic and visualization tools are expanded, and new partner organizations are registered, the WCODP and WCODN will continue to grow to better inform management and planning decisions at a regional scale.

Acknowledgments

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Supplemental Resources

Dawn J. Wright, ed.; 2016; *Ocean Solutions, Earth Solutions*, second edition; http://dx.doi.org/10.17128/9781589484603_9d

For the digital content that goes with this chapter, listed as follows in this section, go to the book's online resources (esri.com/esripress-resources/ocean-solutions-2e). Links and QR codes are provided here for additional ocean resources.

Ocean and Coastal Resources

The online resources for chapter 9 include the following:

- WCGA “West Coast Ocean Data Sharing Best Practices and Policies” PDF
- “WCGA RDF (Regional Data Framework)) Data Registry Design Assessment” PDF
- OOI Cables Metadata XML
- Solr Schema Metadata XML

Additional Ocean Resources

For additional ocean resources, go to the following links:

- West Coast Ocean Data Portal, <http://portal.westcoastoceans.org>



- Action Coordination Team website, <http://www.westcoastoceans.org/wcodp>



- GitHub Repository, <https://github.com/ECOTRUST/wc-data-registry>



- Geoportal Facets Customization GitHub Repository, <https://github.com/Esri/geoportal-server/wiki/Geoportal-Facets>



- Apache Solr, <http://lucene.apache.org/solr>



CHAPTER 10

Linking Landscape Condition Impacts to Coral Reef Ecosystem Composition for the East End of Saint Croix

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Abstract

In this land-sea characterization, we endeavored to map spatial patterns of the connections between actions on land and impacts at sea. Specifically, we analyzed 2007 land-cover data, evaluated land-use patterns, and applied a Landscape Development Intensity Index for watersheds adjacent to the East End Marine Park of Saint Croix, US Virgin Islands. We then correlated the distribution of benthic species and coral reef habitats within 300 m buffer watershed impact zones of the landscape development intensity index to identify and explore potential linkages between land-use patterns and ecological impacts on coral reefs. We compared the benthic habitat composition of watershed impact zones within classes of anticipated impacts from land-based sources of pollution. This analysis uses benthic habitat data, both from benthic habitat maps and in-water surveys. The benthic habitat maps indicate a positive correlation between the Landscape Development Intensity Index and seagrass presence and a negative correlation between the index and coral cover. The in situ surveys reveal higher coral cover in medium-impact classes compared with high and low impact. Although the results from comparing benthic habitat maps and in situ surveys are inconsistent, we anticipate that this may be because of the low number and uneven distribution of the in-water surveys. Additionally, we identified watersheds in which species known to be susceptible to land-based sources of pollution are located. The process described here is intended to evaluate potential linkages between the landscape condition and marine ecosystem condition. We expect that the methods described here can also be employed to track the impacts of land-based sources of pollution on benthic habitats and species composition in the nearshore environment.

Introduction

Coral reefs are among the most diverse and productive ecosystems on Earth. In many locations they are the economic engine of the marine environment, providing a wide range of ecosystem goods and services, including food, as well as supporting recreation and tourism activities, and offering coastal protection from storm and wave action. The total annual economic value of coral reef services to the United States is estimated at US\$3.4 billion (Brander and Van Beukering 2013), with coral reefs of the US Virgin Islands valued at approximately US\$187 million annually (Van Beukering et al. 2011).

The United States and its territories are home to thousands of acres of coral reefs that stretch from remote, relatively untouched areas in the Pacific Ocean to densely populated regions in the Caribbean Sea and Atlantic Ocean. With their vibrant colors and array of fish, sea grass, and invertebrates, coral reef ecosystems are the foundation of many unique and special places throughout the country. The US Virgin Islands contain two coral reef national monuments, a national park, and several territorial marine protected areas, including the East End Marine Park on the island of Saint Croix, to enhance protection of coral reef ecosystems.

Despite their economic, biological, and cultural significance, coral reefs in the US Virgin Islands and those across the globe face a myriad of threats and stressors, such as storms, thermal stress from elevated water temperature, diseases, and land-based sources of pollution (Rogers and Beets 2001). Research indicates that multiple threats and stressors interact to negatively impact coral reefs, and poor water quality from runoff reduces the resilience of corals to disturbance from thermal stress (Carilli et al. 2009; Ban et al. 2014).

Coastal development and land-based sources of pollution, such as runoff, are a major concern to marine resource managers in the US Virgin Islands and other small islands, where steep terrain results in direct and rapid transport of runoff into coastal waters after rainfall events (Smith et al. 2008; Waddell and Clarke 2008). In these environments, unpaved “dirt” roads in the watershed are identified as a major source of sediment onto reefs (Begin et al. 2014).

These land-sea connections are of particular interest to coastal resource managers of the Saint Croix East End Marine Park, where the upland development of watersheds poses a primary threat to the health of adjacent marine ecosystems. This concern is documented in the management plan for the East End Marine Park (The Nature Conservancy 2002). The Saint Croix East End Marine Park, established in 2003 as the first multiuse marine park managed by the US Virgin Islands Department of Planning and Natural Resources, encompasses nearly 39,000 acres of underwater habitats and protects the largest island barrier reef system in the Caribbean. Geographical patterns of predicted erosion suggest that the eastern half of Saint Croix is more seriously impacted than the west. The eastern half is also where considerable long-term investments have been made to protect coral reef ecosystems through establishment of marine protected areas by federal and territorial governments supported by nongovernmental organizations and community groups.

At the time of the park’s establishment, there were substantial data gaps in knowledge about the living marine resources, watersheds, and environmental interactions that influence the park’s marine resources. To address these data gaps, the government of the US Virgin Islands requested the support of the National Oceanic and Atmospheric Administration (NOAA) National Centers for Coastal Ocean Science (NCCOS) to characterize

- the condition of the landscape and adjacent seascape relative to threats to coral reef ecosystem condition; and

- the marine communities within the Saint Croix East End Marine Park boundaries, to increase local knowledge of the resources exposed to various stressors.

This chapter provides a synopsis of the land-sea characterization of the Saint Croix East End Marine Park. It describes the calculation and mapping of the landscape development intensity index (LDII) as a spatial proxy for evaluating the threat from runoff and analyses of biotic communities within watershed impact zones (WIZs) associated with each watershed. The focus is on examining and identifying locations in which vulnerable species are exposed to threats from land-based sources of pollution and providing a baseline for tracking potential changes in habitat composition. Pittman and colleagues (2013) make a comprehensive report on the land-sea characterization of the Saint Croix East End Marine Park.

Background

Alteration of the natural landscape for development, road construction, and agriculture can have adverse impacts on coral reefs through increased delivery of sediment and pollution to coastal waters. The threat associated with land clearing is higher in areas of steep relief, intense precipitation, and where soils are erosive in nature (World Resources Institute and NOAA 2006). Our land-sea characterization seeks to highlight potential linkages between land-based sources of pollution (LBSP) and the condition of coral reef ecosystems for the East End Marine Park by building on previous efforts to help managers prioritize actions and guide local action strategies. Specifically, we quantified and mapped the watershed condition in the landscapes in closest proximity to the Saint Croix East End Marine Park, and then examined spatial distribution patterns of marine communities and potentially vulnerable species to determine the relative coral reef condition.

Previous studies have characterized spatial patterns in stressors and threats to coral reef ecosystems, but only a few studies have examined landscape condition as a proxy for threats to coral reefs and linked assessment of ecological condition of coral reef ecosystems to adjacent watersheds. Burke and colleagues (2011) analyzed coastal development, watershed-based pollution, marine pollution and damage, and overfishing to characterize factors that affect coral reef ecosystems and categorized the US Virgin Islands as experiencing “high” levels of exposure to threats from local human activities. Exposure to threats increased even further when projected climate change stressors (sea temperature and acidification) were included in the risk assessment. Another study analyzed the relative erosion potential of watersheds as well as estimated erosion from roads, and found that the majority of the eastern end of Saint Croix is highly vulnerable to land erosion (World Resources Institute and NOAA 2006).

To address increasing concerns about watershed condition, the NOAA Coral Reef Conservation Program commissioned two projects by Horsley Witten Group to assess threats from land-based sources of pollution to watersheds adjacent to the Saint Croix East End Marine Park. The first document, *St. Croix East End Watersheds Existing Conditions Report* (Horsley Witten Group 2011a), identifies basic watershed characteristics such as soils, rainfall, land use, and infrastructure. It also examines individual sites, the potential for reduction in land-based sources of pollution, and the feasibility of implementing restoration projects. Several restoration projects are highlighted as priorities for implementation. Building on watershed restoration activities associated with the American Recovery and Reinvestment Act of 2009, the NOAA Coral Reef Conservation Program, US Virgin Islands Department of Planning and Natural Resources, US Department of Agriculture,

and The Nature Conservancy are coordinating comprehensive watershed restoration plans for six watersheds that surround the park. Some of these watersheds are 303(d)-listed impaired water bodies. In the second report, *St. Croix East End Watersheds Management Plan* (Horsley Witten Group 2011b), one objective was to protect marine resources by reducing the negative impacts of land-based sources of pollution through reducing sediment and nutrient loads. The Watersheds Management Plan focuses on actions that can be taken on land to reduce negative impacts to marine ecosystems and natural resources.

In 2011, a team of scientists with the US Environmental Protection Agency applied an index of human disturbance to correlate landscape development with nearshore marine ecosystem conditions in Saint Croix (Oliver et al. 2011). Their analysis focuses on the relationship between impervious surfaces and coral reef assemblage metrics such as stony coral colony density, taxa richness, coral colony size, and total coral cover. The LDII, an index of human disturbance, quantified impervious surfaces, agriculture, and other land-cover types to create a composite value for each watershed and represents a spatial proxy of the potential threat to water bodies from runoff. Oliver and colleagues (2011) found that the LDII is more robust than other indicators of human activity and correlates negatively with stony coral colony density, taxa richness, colony size, and total coral cover. The LDII was also an effective indicator of human impacts to corals, and highlights the link between land-based human activity and marine ecosystems.

For this study, we adapted and applied the LDII techniques developed by Oliver et al. (2011). However, we expanded the LDII to include the additional variable of “dirt roads.” Furthermore, we correlated the LDII to coral-cover metrics to highlight areas in which human-impacted terrestrial conditions are close to high-priority marine species, habitats, and biodiversity hot spots.

Methods

The US Virgin Islands recognizes six watersheds, encompassing a total area of 3,145 ha, that make up the land adjacent to the park. These watersheds range in size from 807 ha for Great Pond Bay to 281 ha for Turner Hole, and were too coarse for the scale of this analysis. To examine potential linkages between land-based sources of pollution and ecological condition of coral reef ecosystems, we used the island’s stream network and aerial photographs to aggregate 121 catchment basins, which were identified using the US Geological Survey (USGS) National Hydrography Dataset (NHD), into 42 watershed units.

One of the primary contributors to land-based sources of pollution is erosion from land-cover conversion. To analyze the potential contribution to sedimentation for each analytical unit, we analyzed the land-cover data developed in 2007 by the NOAA Office for Coastal Management (formerly the Coastal Services Center) Coastal Change Analysis Program (C-CAP) (figure 10.1). Our analysis applied the LDII developed by the Center for Environmental Policy of the University of Florida (Brown and Vivas 2005) (table 10.1). The index is intended to serve as a measure of human disturbance. It is calculated on the basis of the level or density of human activity in a given area based on land-cover properties. The LDII quantifies impervious surfaces, agriculture, and other land-cover types to create a composite value for each watershed, forming a spatial proxy of potential threat to nearshore waters from runoff. Oliver and colleagues (2011) first linked the landscape development intensity index to coral reef condition along the coast of Saint Croix. The researchers found that the LDII was more robust than other indicators of human activity, exhibiting negative correlations with stony coral colony density, taxa richness, colony size, and total coral cover. The LDII provided

an effective indicator of human impacts to corals, highlighting the link between land-based human activity and marine ecosystems. Using a more recent land-cover product and finer scale watershed units focused only on Saint Croix East End Marine Park, we modified the approach of Oliver and colleagues (2011) by incorporating dirt road density into the LDII. Our approach quantified and ranked landscape development intensity for each watershed unit, and then identified areas in which high-intensity landscape development is likely to threaten sensitive marine species and habitats.

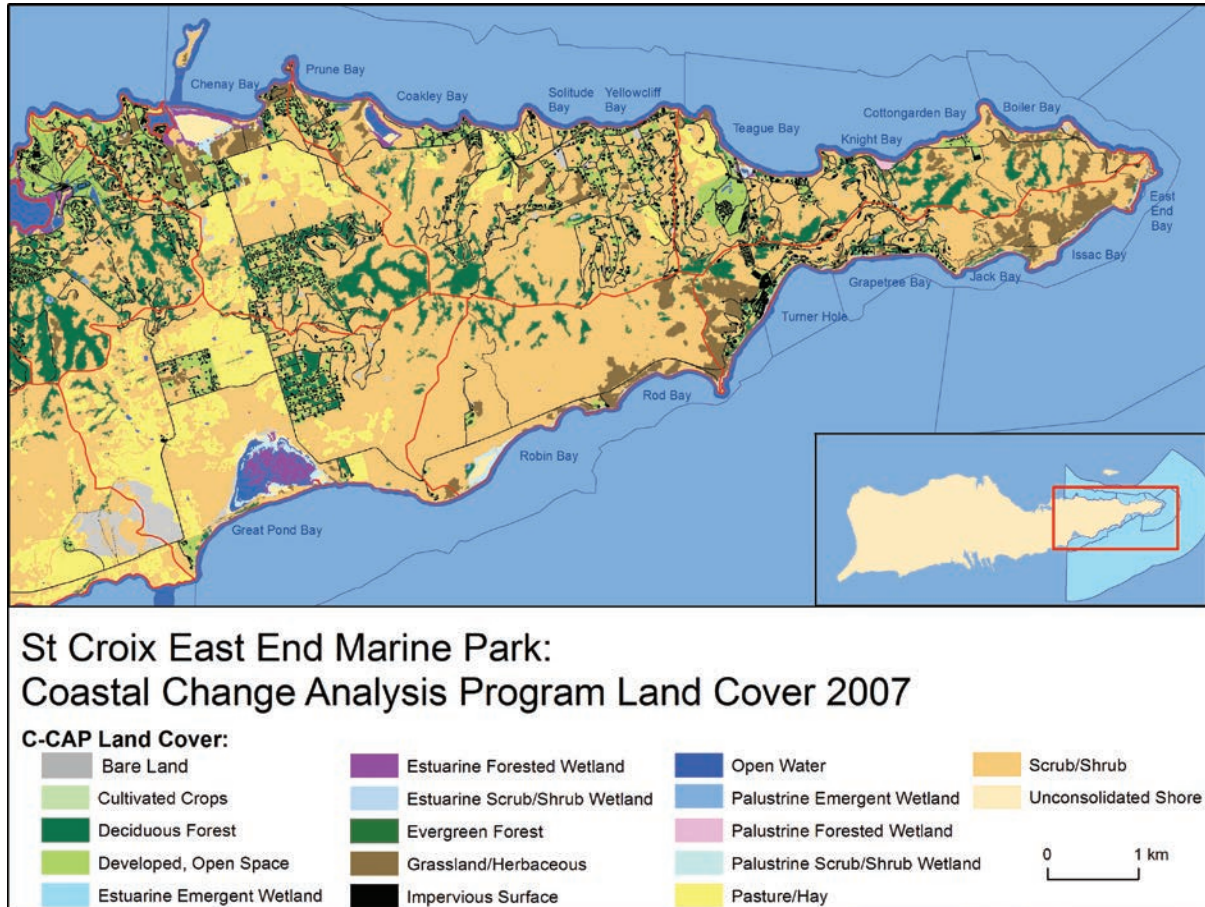


Figure 10.1. Land-cover map developed by the Coastal Change Analysis Program of the National Oceanic and Atmospheric Administration Office for Coastal Management, formerly the Coastal Services Center.

Map by authors; data source: NOAA NOS Office for Coastal Management (formerly Coastal Services Center) Coastal Change Analysis Program.

Table 10.1. Landscape Development Intensity Index Coefficients

Land Cover Class	Landscape Development Intensity Index Coefficient
Impervious Surface	8.28
Pasture/Hay	3.03
Grassland/Herbaceous	2.06
Scrub/Shrub	2.06
Bare Land	1.85
Developed, Open Space	1.85
Deciduous Forest	1.00
Palustrine Forested Wetland	1.00
Palustrine Scrub/Shrub Wetland	1.00
Palustrine Emergent Wetland	1.00
Estuarine Forested Wetland	1.00
Estuarine Scrub/Shrub Wetland	1.00
Estuarine Emergent Wetland	1.00
Unconsolidated Shore	1.00
Open Water	1.00

Table by authors; data source: EPA.

We created WIZs adjacent to the watersheds of the Saint Croix East End Marine Park (figure 10.2). The WIZs were constructed using a 300 m buffer along the coast of the park that was then subdivided into smaller areas immediately adjacent to the watershed units. The zones were used as replicate sample units to determine potential effects of land-based sources of pollution on marine biota. A buffer of 300 m was selected based on the likelihood that impacts from land-based sources of pollution to marine biota are detectable within 300 m of the land-sea interface. We acknowledge that land-based sources of pollution can influence a broader geographical extent because local water movements can disperse terrigenous materials offshore and alongshore beyond 300 m. However, impacts from land-based sources of pollution on marine biota are likely to decrease with increasing distance from shore because of dilution. Therefore, our WIZs represent conservative regions of impact, within which marine biota most likely will be exposed to land-based sources of pollution. In addition, the intensity of a threat from land-based sources of pollution was included by weighting the WIZs with LDII values to account for spatial variability in land development within the study area.

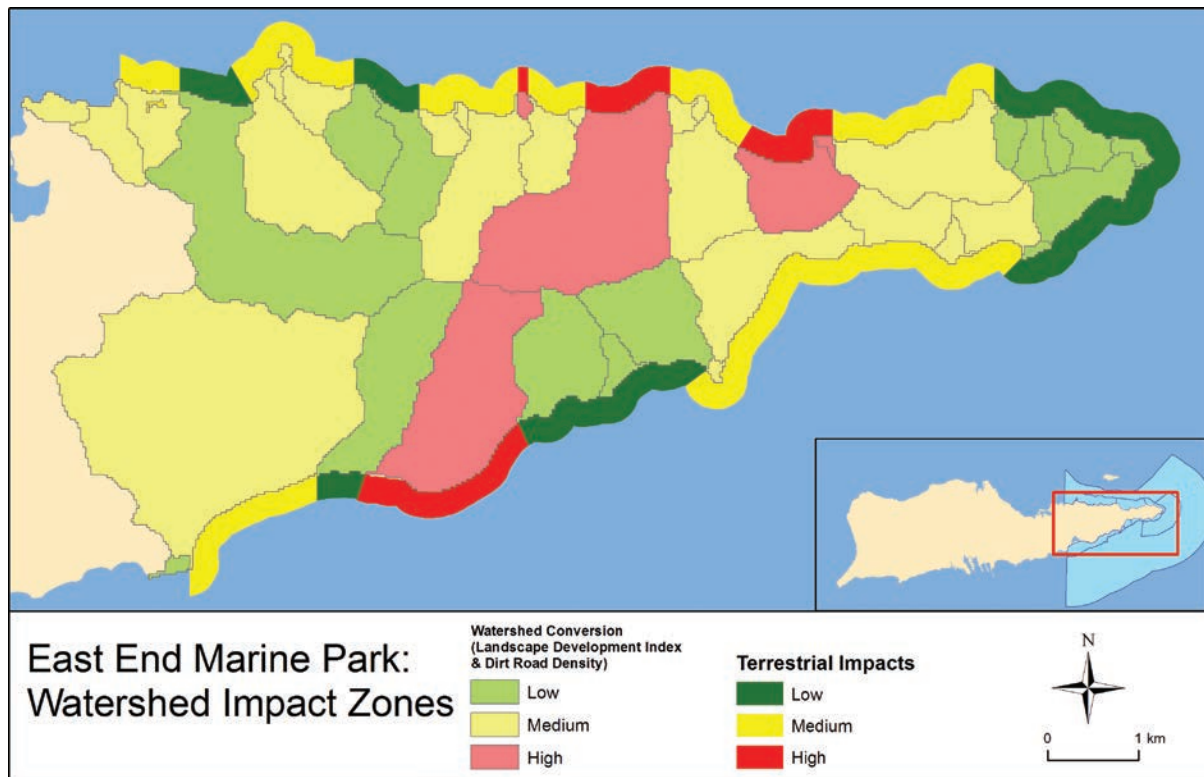


Figure 10.2. Terrestrial impacts and watershed impact zones. Map by authors; data source: NOAA National Centers for Coastal Ocean Science.

LDII provides one measure of the expected threat to coastal ecosystems from watershed-based pollution. Another expected threat is soil erosion from dirt roads. This threat was not captured by the LDII, so it was characterized independently. The area of dirt roads mapped by Horsley Witten Group was quantified for each analytical unit and used as a proxy for soil erosion from dirt roads. Horsley Witten Group interpolated 2009 aerial orthophotos and parcel boundaries as part of the Saint Croix East End Watershed Planning effort funded by the NOAA Coral Reef Conservation Program (Horsley Witten Group 2011a, 2011b). Road type was verified during January 2011 field assessment work (Horsley Witten Group 2011a). The LDII and dirt road variable were combined to create a single metric that represents potential negative impacts to nearshore habitats (see figure 10.2). Figure 10.3 summarizes the process used to map and link land-based stressors to adjacent WIZs.

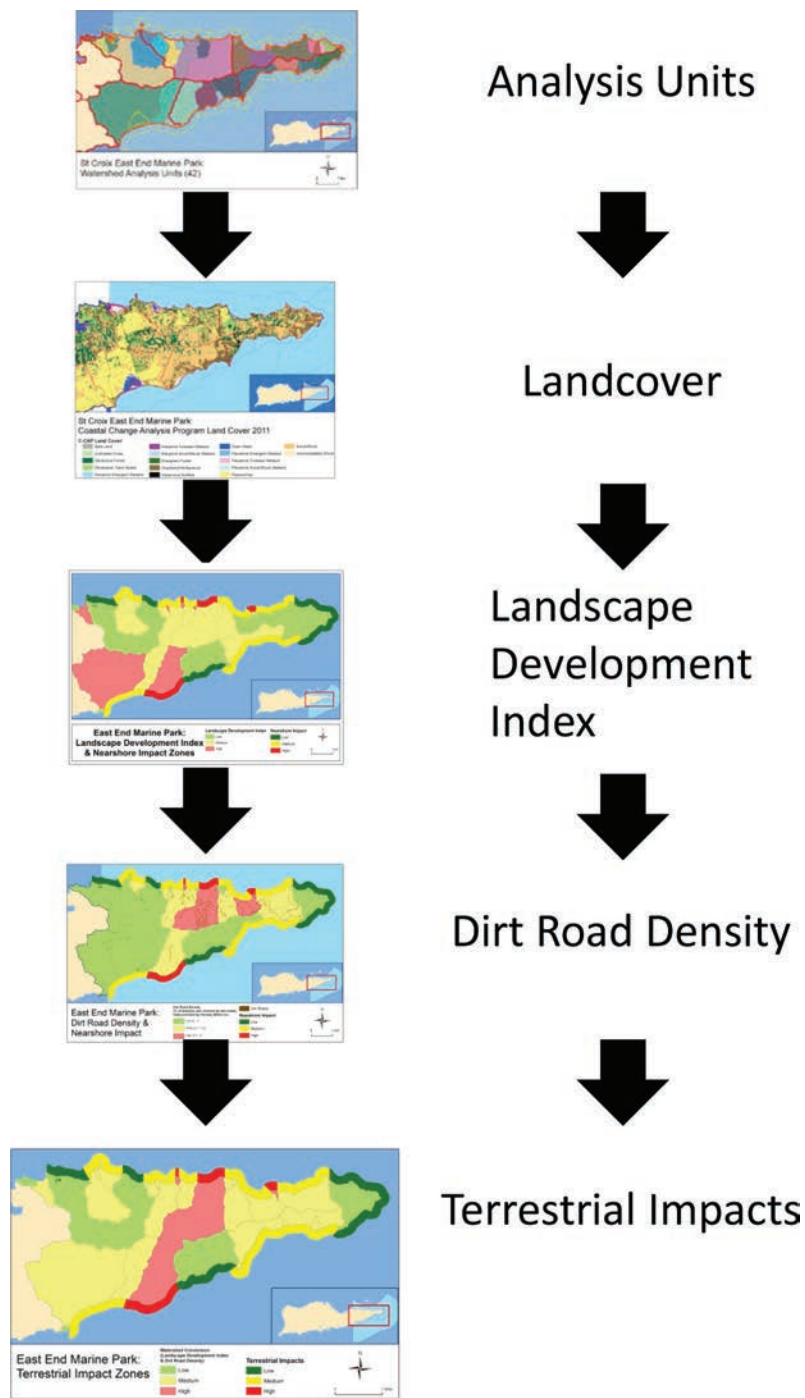


Figure 10.3. Analytical process for deriving terrestrial impacts to watershed impact zones. Map by authors; data source: NOAA NOS Office for Coastal Management (formerly the Coastal Services Center) Coastal Change Analysis Program and Horsley Witten Group.

Characterization of Marine Benthic Communities in Watershed Impact Zones

Benthic habitats were evaluated using two distinct datasets: (1) benthic habitat maps developed by the NOAA Coral Reef Conservation Program (Kendall et al. 2002), and (2) direct observation conducted by underwater surveys. Information from NOAA benthic habitat maps was analyzed to quantify the composition and area of habitat types (e.g., sea grasses, coral reef, sand) in each zone. This data provides managers with information on the proportions of each habitat type within each management unit. Benthic habitats were digitized from high-resolution aerial photographs, and their accuracy was assessed using underwater validation surveys (Kendall et al. 2002).

In addition to the information collected from benthic maps, we used a 10-year (2002–10) dataset of in situ, field-based observations of benthic composition from direct observation, using 251 point locations to describe benthic communities within each WIZ, as well as management zones within the park. In situ variables analyzed from this study were the percentage cover of scleractinian corals, hydrocorals, algae gorgonians, sponges, and sea grasses. Datasets were collected with a stratified random sampling design to comprehensively assess faunal populations and benthic communities around Buck Island Coral Reef National Monument and the Saint Croix East End Marine Park (Menza et al. 2006; Pittman et al. 2008). Point locations were selected randomly from two strata based on benthic habitat maps of the area (Kendall et al. 2002). The “hard” stratum comprised bedrock, pavement, rubble, and coral reefs. The “soft” stratum comprised sand, sea grasses, and macroalgal beds. A subsample of the data was analyzed by selecting only sites that are located within the WIZs of the park ($n = 190$; figure 10.4).

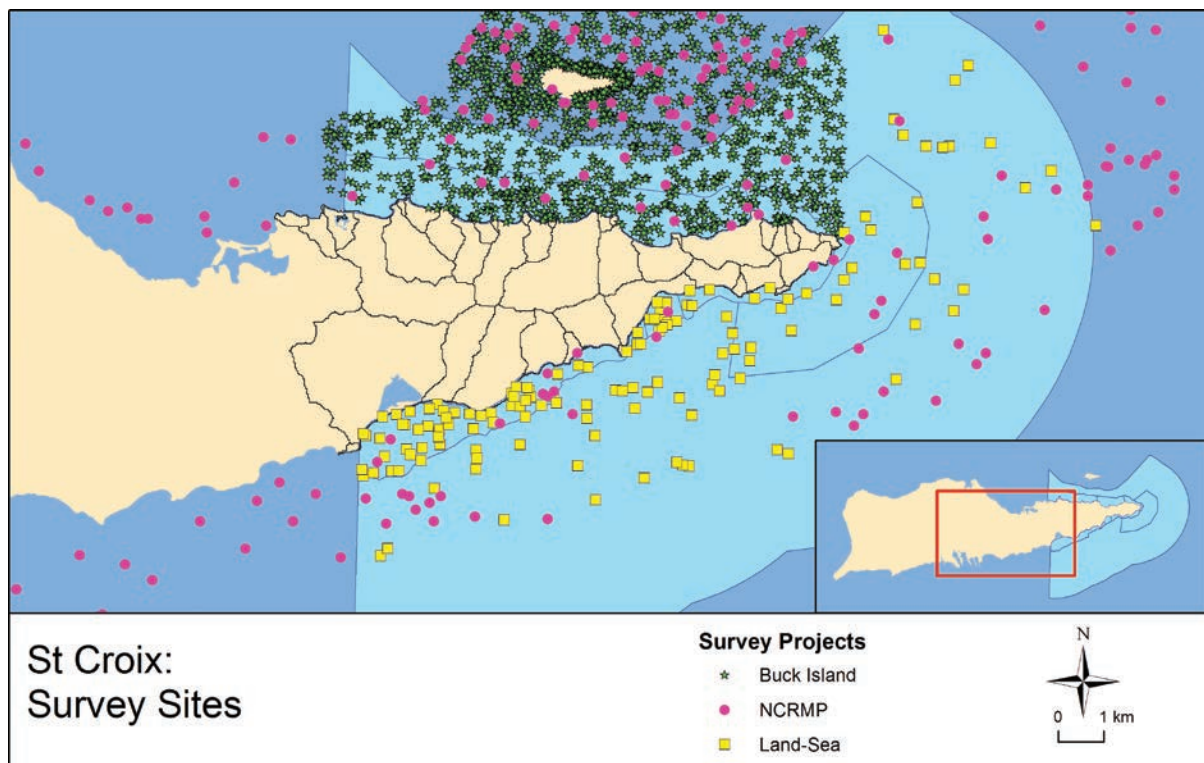


Figure 10.4. Survey locations. Map by authors; data sources: NOAA National Centers for Coastal Ocean Science.

Coral species that are considered sensitive to land-based sources of pollution were selected based on published literature (Bak and Elgershuizen 1976; Rogers 1983; Pastorok and Bilyard 1985; Gleason 1998; Nemeth and Nowlis 2001; Pait et al. 2007). Although observed seagrass species were not considered sensitive to contamination or sedimentation for this study, when exposed to nutrient enrichment or eutrophication sea grasses experience changes in growth rates and relative dominance among species (Fourqurean et al. 1995; Ferdie and Fourqurean 2004; Burkholder et al. 2007).

Results

Marine Communities in the Watershed Impact Zones

Benthic Communities

Analysis of the benthic habitat maps indicates that coral areas are concentrated along the eastern end of the park, while sea grasses and macroalgae dominate the western side (figure 10.5). We analyzed benthic habitat composition as reported from the benthic habitat maps for differences among the impact classes (Kendall et al. 2002) (figure 10.6). We found significant differences between high-, medium-, and low-impact classes for the distribution of coral reef and colonized hard bottom and submerged aquatic vegetation (SAV) habitats. For coral reef and colonized hard bottom, there was a clear trend of greater coral cover in areas with lower anticipated impacts. For SAV, high-impact areas had greater amounts of SAV and low-impact areas had lower levels.

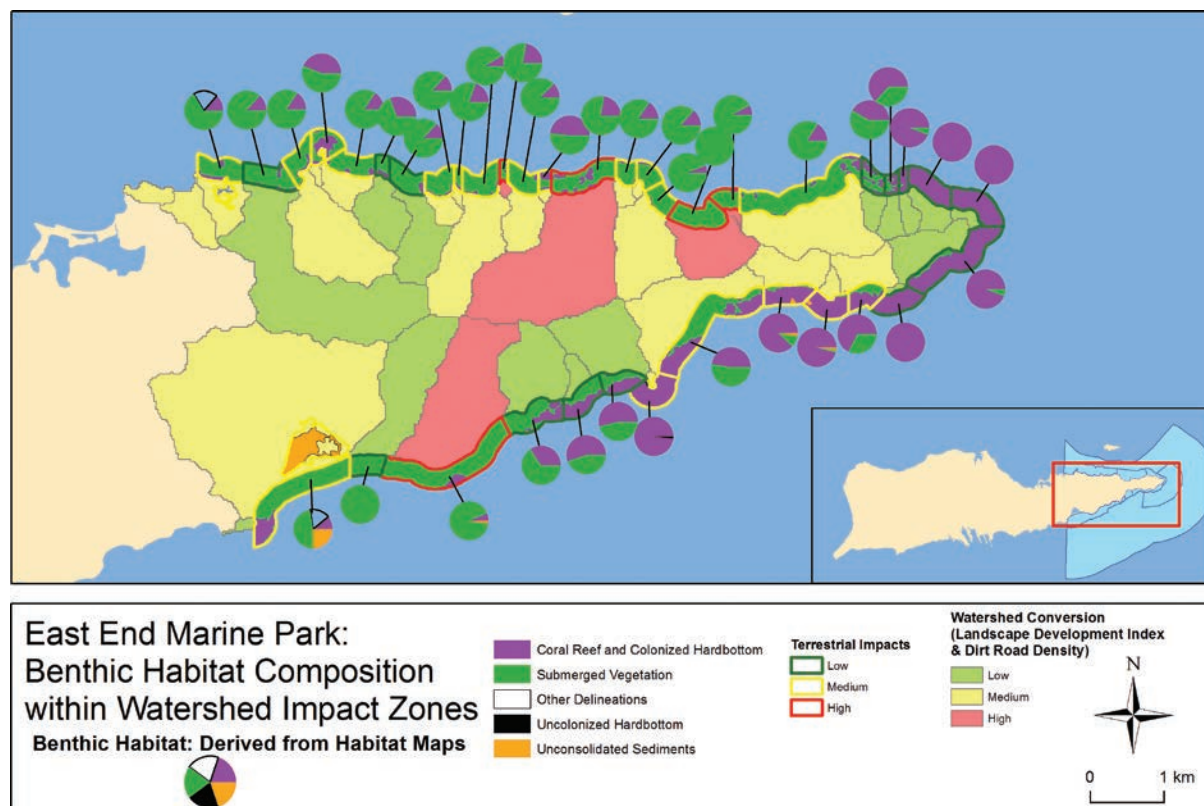


Figure 10.5. Benthic habitats mapped within watershed impact zones. Map by authors; data source: NOAA National Centers for Coastal Ocean Science.

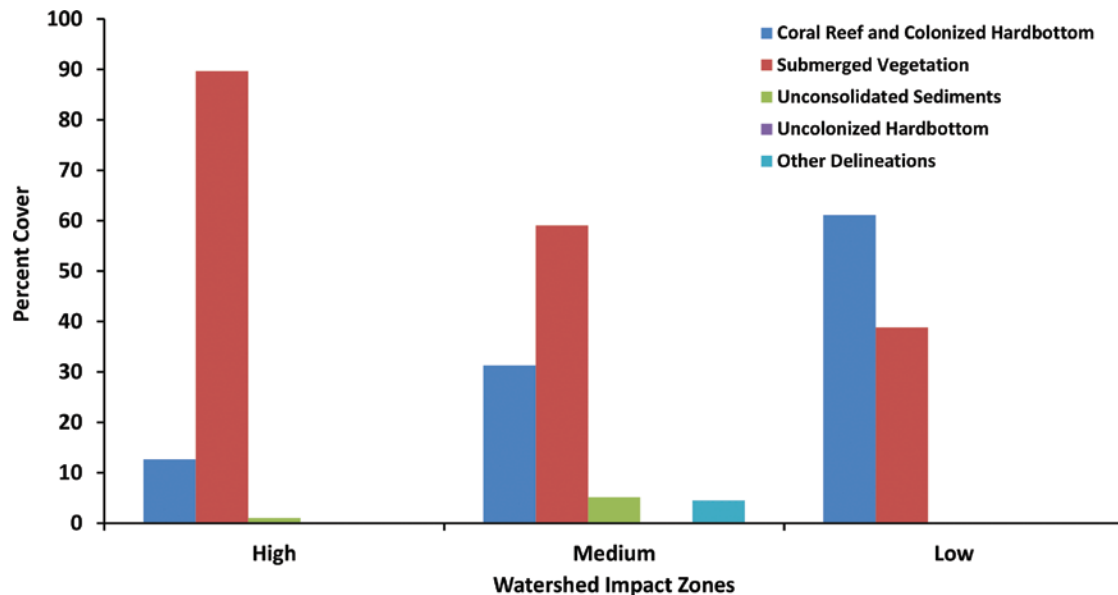


Figure 10.6. Graph of the distribution of habitat types within impact classes. Chart by authors; data source: NOAA National Centers for Coastal Ocean Science.

Based on the underwater surveys, the 300 m buffer contained primarily algae and sea grasses. Very little coral reef was found within the WIZs. The highest coral cover is found in Teague and Boiler Bays on the northeast end of the park. Figure 10.7 shows the composition of benthic habitat types for each of the WIZs, based on information collected through underwater surveys. Figure 10.8 shows benthic habitat composition within each impact class.

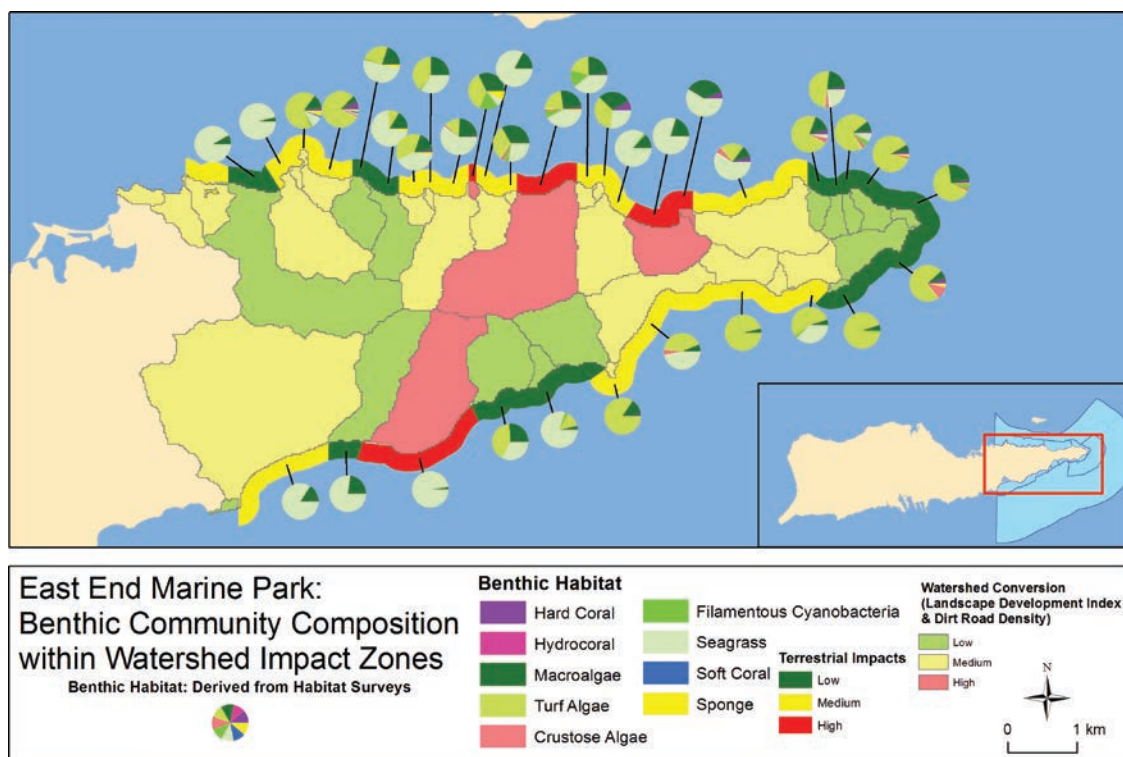


Figure 10.7. Benthic habitat composition as recorded from in situ surveys shown within watershed impact zones. Map by authors; data source: NOAA National Centers for Coastal Ocean Science.

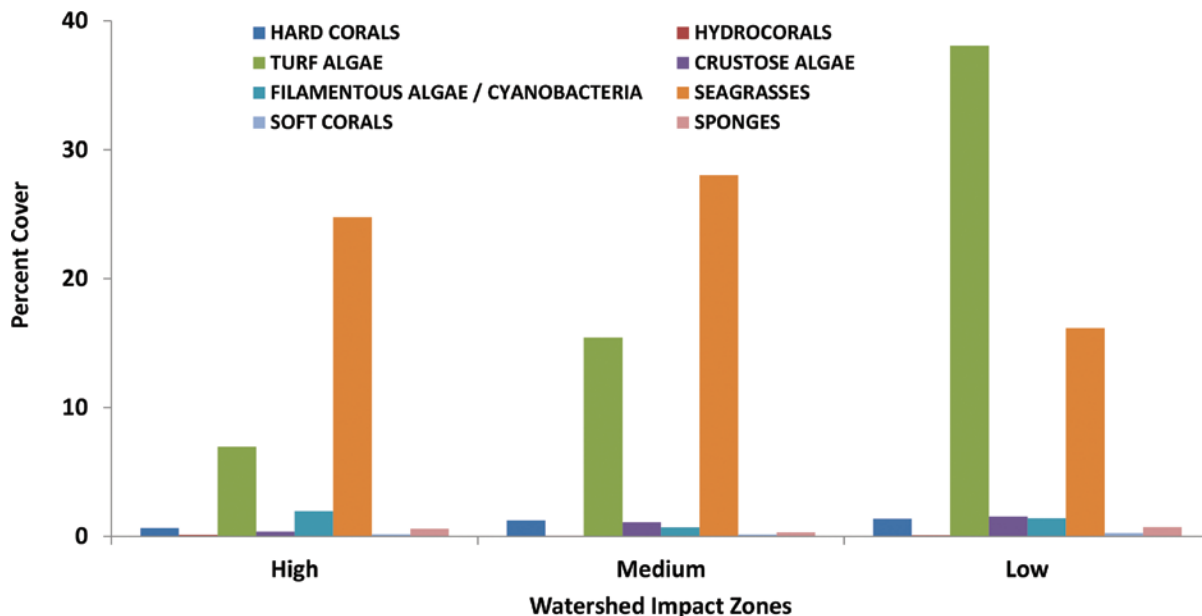


Figure 10.8. Graph of the distribution of habitat types within exposure classes of watershed impact zones based on National Oceanic and Atmospheric Administration underwater surveys. Chart by authors; data source: NOAA National Centers for Coastal Ocean Science.

Significant differences were detected among impact classes for three habitat types: hard corals occurring on hard substrate, turf algae on hard substrate, and hard corals in areas dominated by soft substrate. For hard corals occurring on hard substrate, the difference between medium impact and low impact was most significant, with hard coral habitats more abundant in areas classified as having medium terrestrial impact. There was also a difference in abundance between medium- and high-impact classes, with lower abundance in high-impact areas. A single site drove both of these results, with nearly 33% coral cover occurring in an area classified as medium impact. This site is found in Boiler Bay. For turf algae on hard substrate, differences were significant between high and low classes and between high and medium classes. Turf algae distribution was greater in low and medium classes than in high. In areas dominated by soft-bottom substrate, significant differences were found between hard coral classes. Specifically, the difference was significant between high and low classes and between medium and low classes. For high-impact zones, the difference was driven largely by a single site, with nearly 2% coral reef and colonized hardbottom cover.

Coral Reef Community

To assess the potential threat to coral species known to be sensitive to impacts from land-based sources of pollution, coral locations were mapped within the WIZs (300 m coastal buffer; figure 10.9). Elkhorn coral (*Acropora palmata*), a species listed in the Endangered Species Act (ESA), exists within the WIZs, primarily concentrated on the eastern tip of the island where watersheds are least developed. Staghorn coral (*Acropora cervicornis*) was not sighted within any of the WIZs.

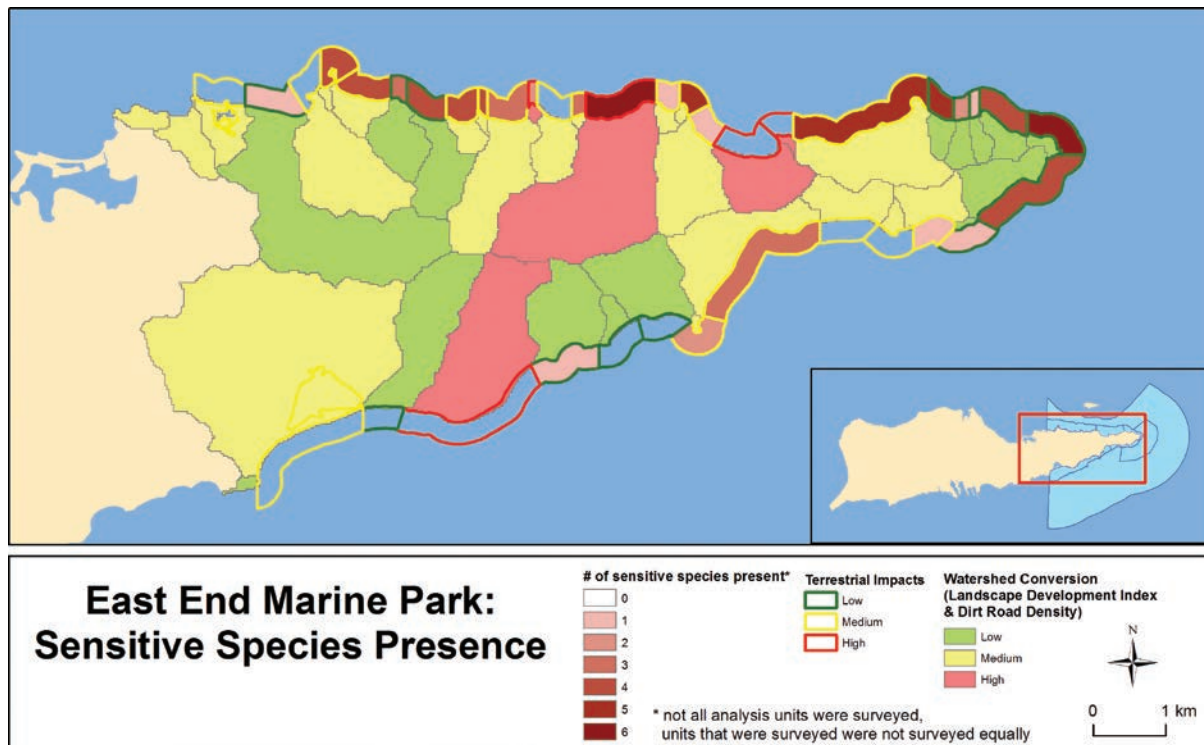


Figure 10.9. Sensitive species distributions within watershed impact zones. Map by authors; data source: NOAA National Centers for Coastal Ocean Science.

Brain coral (*Pseudodiploria strigosa*) was observed in 20 of 38 WIZs. Golfball coral (*Favia fragum*) was observed in 12 impact zone units along the north shore, and boulder star coral (*Orbicella annularis complex*) was observed in six units along the north shore. Yellow pencil coral (*Madracis auretenra*) was not observed within the impact zone. Finger coral (*Porites porites*) and mustard hill coral (*Porites astreoides*) were observed within 20 m and 17 m of the surveyed impact zone units, respectively. No significant differences were detected between threat classes when data on the distribution of sensitive coral species was combined (*Acropora palmat*, *Pseudodiploria strigosa*, *Favia fragum*, *Orbicella annularis complex*, *Madracis auretenra*, *Porites porites*, and *Porites astreoides*).

Many of the WIZs contain species that are known to be sensitive to sedimentation and land-based sources of pollution. Highest species richness for coral sensitive to sedimentation and pollution is found on the north shore of the park with varied exposure to threat (see figure 10.9). The Yellowcliff Bay watershed, which contains six sensitive species, is estimated to be high threat, and several medium-threat impact zones along the northeast shore contain at least five species.

Sea grasses

Shoalgrass (*Halodule wrightii*) was observed in three WIZs. Paddle grass (*Halophila decipiens*) is known to be sensitive to land-based sources of pollution and was not observed in any of the analysis units. Manatee grass (*Syringodium filiforme*) was observed in 27 analysis units. Turtle grass (*Thalassia testudinum*) is widely distributed within the WIZs.

Discussion and Conclusion

On Caribbean islands, land-use patterns are an important concern to the conservation of coral reef ecosystems. Modifications to watersheds such as urbanization and agriculture have the potential to greatly increase erosion and sediment delivery to coastal waters. Many coral species are highly sensitive to declines in water quality caused by runoff of material from land. In response, best practices in management of land development are being introduced to reduce erosion and runoff of land-based sources of pollution into coastal waters. The land-sea characterization presented here provides a technique to prioritize areas for management attention in which potential threat to sensitive coral species is greatest.

We recognize that activities on land can influence the health of nearshore marine ecosystems. In particular, we understand that sedimentation and pollution delivered from land to coral reef ecosystems can kill corals and, by extension, negatively affect entire ecosystems. Certain species of corals are particularly susceptible to pollution and sedimentation. In this study, we highlight areas within the Saint Croix East End Marine Park in which some of these species are present. The recognition of areas in which sensitive species are present can assist coral reef managers in reaching their conservation objectives by highlighting the need for terrestrial management upstream of sensitive coral species. By reducing land-cover conversion and/or road development upstream of sensitive species, we can improve survival conditions for coral species of concern.

This study does not address the issue of how pollution or sediments are transferred from land to sea. It also does not address the complicated issue of exactly where benthic communities will be influenced by upstream watershed conditions. This study identifies areas that are expected to produce high levels of pollution and sediment and evaluates the composition of benthic communities associated with the areas expected to be impacted. When the Saint Croix East End Marine Park was established, it was recognized that the health of the ecosystems that the park was designed to protect would depend on both marine ecosystem management and management of the land adjacent to the park. Here, we hope to have identified one mechanism by which we can associate land-based management with its effects on nearshore marine ecosystems.

In this study, we found inconsistent results between our analysis of habitats from benthic maps and in-water surveys. From the mapped benthic habitats, we found coral cover decreasing where terrestrial impacts are greater and sea grasses increasing with greater terrestrial impacts. However, we did not find the same trend when we evaluated the information collected through underwater surveys. Here, we found greater coral cover in areas with medium terrestrial impacts. We expect that this discrepancy is a result of the limited number and uneven geographic distribution of the surveys taken. The results of the survey information analysis appear to be driven by a single record, in which coral cover was recorded as 33%. This value is significantly different from the average value of 1.18% coral cover across the 190 surveys. We expect that greater survey effort and a more even geographic distribution of surveys might enable us to better track the impacts of terrestrial influence to direct observations of the benthic community.

Acknowledgments

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Supplemental Resources

Dawn J. Wright, ed.; 2016; *Ocean Solutions, Earth Solutions*, second edition; http://dx.doi.org/10.17128/9781589484603_10d

The digital content for this chapter, listed in this section, can be found in the book's online resources (esri.com/esripress-resources/ocean-solutions-2e). There, you can view and enlarge digital photos of sea life in the East End Marine Park, Saint Croix, US Virgin Islands. The photos were taken between 2007 and 2012 and are courtesy of the NOAA NCCOS Biogeography Branch. The photos include

- Blackbar soldierfish (*Myripristis jacobus*)
- Blue tang (*Acanthurus coeruleus*) in dense gorgonian habitat
- Coral within the park
- Elkhorn coral (*Acropora palmata*), an endangered species
- Finger coral (*Porites porites*)
- Large school of adult and juvenile grunts (family *Haemulidae*)
- Red hind (*Epinephelus guttatus*)
- Scuba divers collecting fish and benthic composition data

CHAPTER 11

Using GIS Tools to Develop a Collaborative Essential Fish Habitat Proposal

Sophie de Beukelaer, Karen F. Grimmer, Jennifer A. Brown, and Chad King

Abstract

In 2012, the Monterey Bay National Marine Sanctuary brought together stakeholders representing different interests (e.g., fishing and conservation) to work toward a collaborative proposal to the Pacific Fishery Management Council for the design of spatial modifications to current Pacific coast groundfish essential fish habitat conservation areas. This redesign involved adding new areas that contain sensitive resources in need of protection from bottom-trawl fishing gear and reopening some areas to gain access to historical fishing grounds of economic importance to bottom-trawl fishermen. The collaborative proposal was submitted in July 2013 after 11 months of work among stakeholders. This accomplishment is largely owed to the use of a suite of GIS tools, including GIS projects and products such as a customized ArcGIS Online map and spatial analysis tools, which helped inform discussions. The project used GIS to provide a clear understanding of the current spatial management, distribution of sensitive resources, and distribution of historical and current fishing efforts. In addition, marine Sanctuary staff used desktop GIS maps during group meetings to manage discussions, enabling the group to move forward even during times of tension and disparity. Data layers were added to help elucidate the topic of conversation or focus the map on a different area to refocus the discussion. At the time of this writing, the proposal was still under consideration by the Pacific Fishery Management Council for implementation. If accepted and approved, the comprehensive essential fish habitat proposal will increase habitat protection for hundreds of known coral and sponge specimen locations, as well as reopen historically important bottom trawling areas in the Monterey Bay National Marine Sanctuary. The collaborating entities that were part of the completed proposal include the Sanctuary, Alliance of Communities for Sustainable Fisheries, Monterey Bay trawl fishermen, the City of Monterey, Oceana, the Natural Resources Defense Council, Ocean Conservancy, The Nature Conservancy, California Risk Pool, and the Environmental Defense Fund.

Introduction

The Monterey Bay National Marine Sanctuary (MBNMS) is a federally protected area offshore of California's central coast. Its boundaries encompass 6,094 sq mi of remarkably productive offshore waters from Cambria to north of San Francisco (figure 11.1). MBNMS is one of 13 national marine sanctuaries in the United States. The goal of the National Marine Sanctuaries Act is to conserve pristine ocean areas for future generations, just as the nation has protected national parks and forests since the 19th century. The National Marine Sanctuaries Act mandates the MBNMS to “maintain for future generations the habitat and ecological services of the natural assemblages of living resources that inhabit” the Sanctuary. In addition to resource protection and conservation, MBNMS was established for the purpose of research, education, and compatible public use.

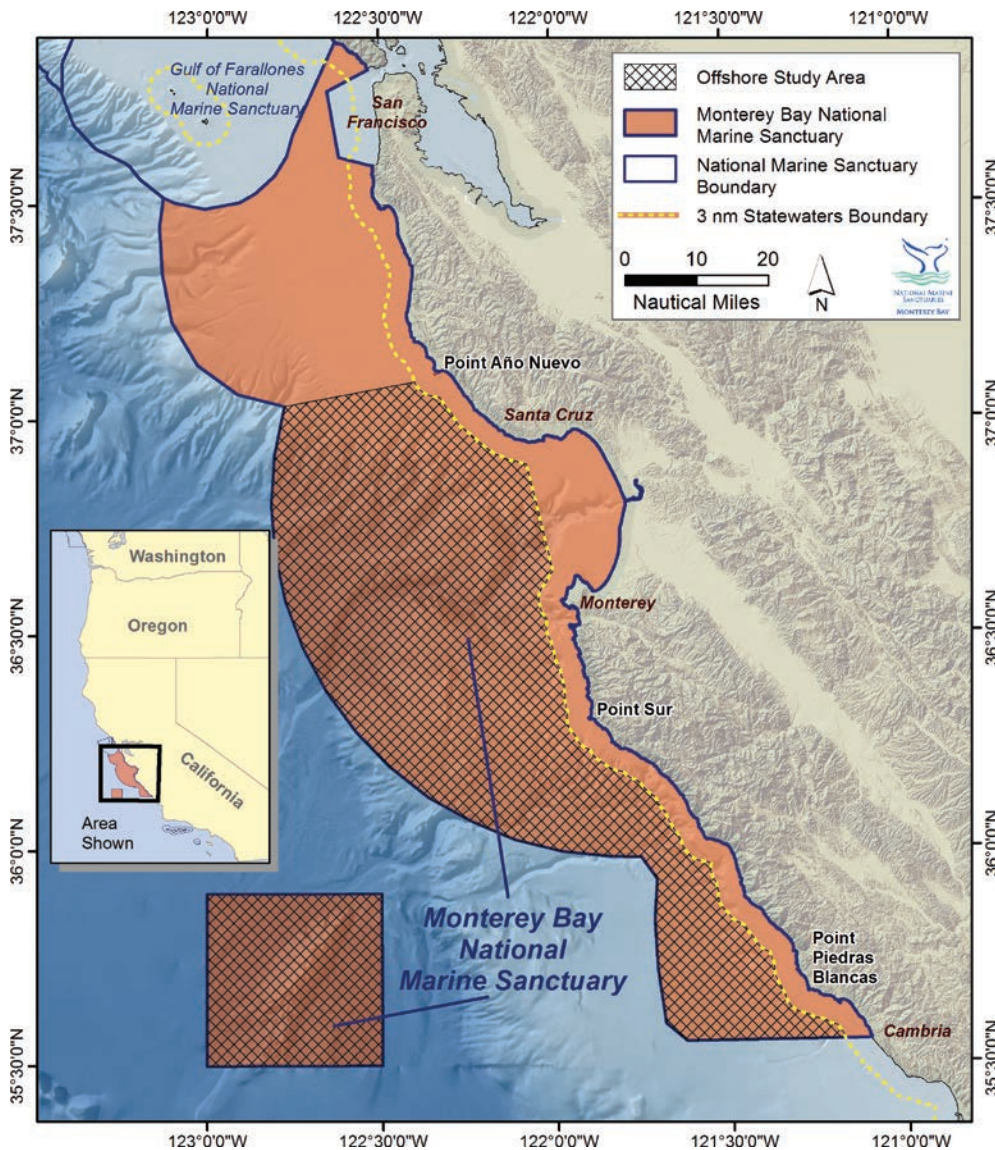


Figure 11.1. Monterey Bay National Marine Sanctuary boundaries and the offshore study area boundary. The offshore study area includes all the Sanctuary south of Point Año Nuevo and west of the 3 nm state waters boundary line. The state waters boundary represents the seaward boundary of the coastal states of the United States. Courtesy of NOAA Monterey Bay National Marine Sanctuary. Data from NOAA, California Department of Fish and Wildlife, Monterey Bay National Marine Sanctuary, Esri; logo courtesy of Monterey Bay National Marine Sanctuary.

Human uses of the Sanctuary include both commercial and recreational activities, such as fishing, whale watching, sailing, diving, kayaking, and surfing. Some human activities that threaten the health of Sanctuary resources, such as oil drilling, ocean dumping, and seabed mining, are not allowed within the Sanctuary. Other human uses that have the potential to impact sensitive resources in the Sanctuary are allowed but managed either directly by MBNMS or other state and federal resource management agencies.

Building partnerships with other resource management agencies and fostering strong public involvement are key elements that help MBNMS attain its management plan goals. For example, the goal of the *Bottom Trawling Effects on Benthic Habitats* action plan, a component of the MBNMS management plan (Office of National Marine Sanctuaries 2008), is to maintain the natural biological communities and ecological processes in MBNMS by evaluating and minimizing adverse impacts of bottom trawling in benthic habitats while allowing the long-term continuation of sustainable local fisheries in MBNMS. Strategies to address that goal include developing partnerships with fishermen, assessing trawling activity, identifying habitats that are vulnerable to trawling, and identifying and implementing potential ecosystem protection measures. MBNMS can only attain those types of goals by working with stakeholders and engaging with partners in natural resource management processes.

MBNMS does not regulate fisheries, but fisheries have an impact on the habitats and ecological services that MBNMS is mandated to protect. Toward that end, MBNMS engages as a partner agency and stakeholder in the various fishery management processes led by state and federal fisheries management agencies. For example, the National Marine Fisheries Service (NMFS) and Pacific Fishery Management Council (PFMC) use a variety of methods, such as quotas, trip limits, gear restrictions, and permanent and time-area closures, to regulate fishing in the United States; and a variety of management processes are used to identify and implement these management strategies. One type of permanent area closure is the Pacific coast groundfish essential fish habitat (EFH). MBNMS staff and partners engaged in the first EFH review process after the EFH designation was established in 2006.

NMFS and PFMC established EFH boundaries for groundfish and habitat areas of particular concern (HAPCs) in 2006 in Amendment 19 to the Magnuson-Stevens Act (Office of the Federal Register 2006) to fulfill the requirements for EFH established by the act. EFH is defined as those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity. The entire US West Coast continental margin was designated as EFH, but this designation alone did not include any fishing restrictions. Rocky reefs, for example, were designated as HAPCs because of their importance to groundfish, their rarity in the region, and their sensitivity to impacts, but that designation alone did not provide protection either. EFH conservation areas, however, are areas that are permanently closed to certain types of bottom-contact gear to protect groundfish EFH and HAPCs. In 2006, NMFS and PFMC established 51 conservation areas offshore of the US West Coast, including three areas either wholly or partially in MBNMS (figure 11.2). However, key stakeholders were not at the table when these large conservation areas were designed.

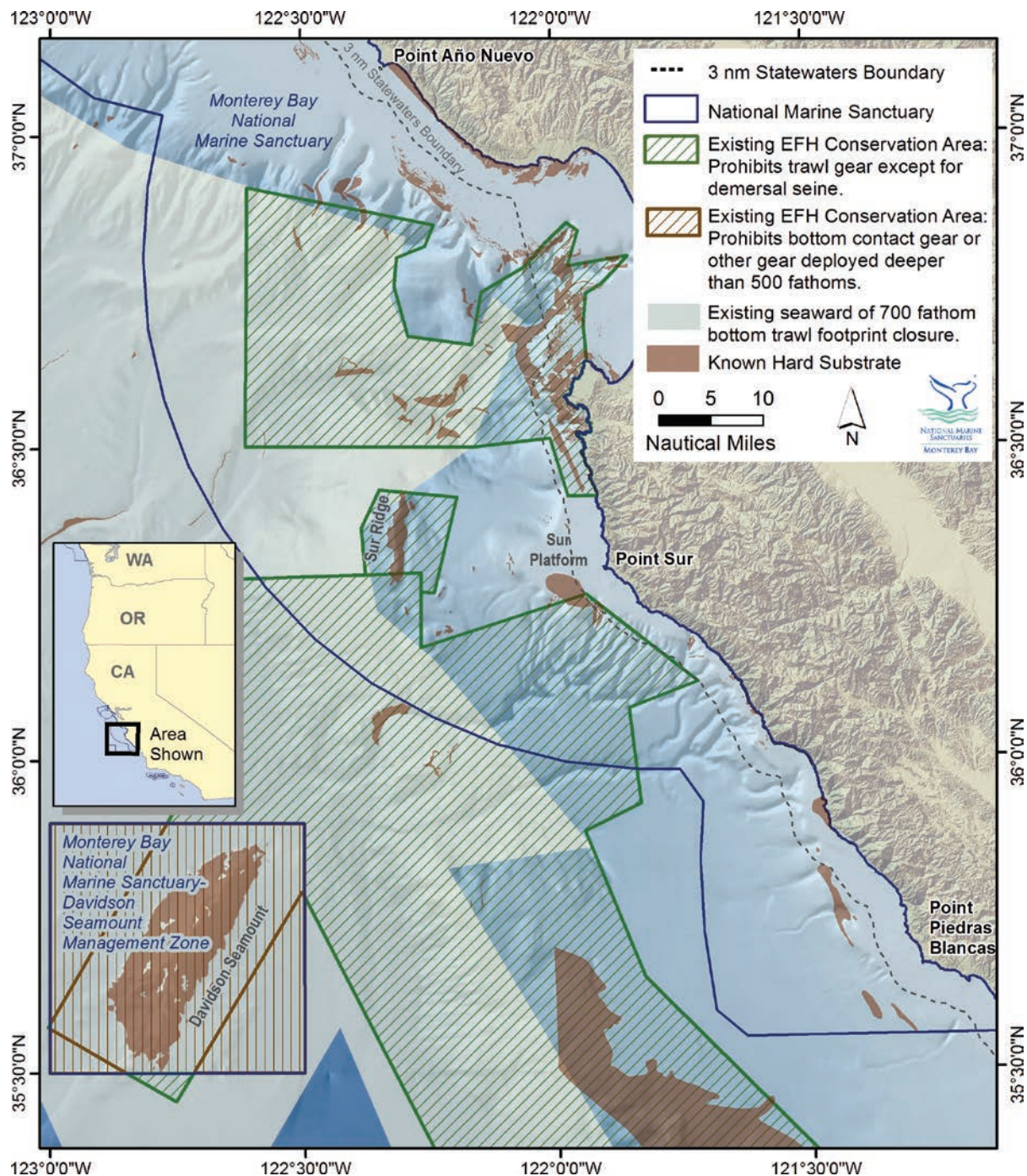


Figure 11.2. Essential fish habitat (EFH) conservation areas within the Monterey Bay National Marine Sanctuary. Courtesy of NOAA Monterey Bay National Marine Sanctuary. Data from NOAA National Marine Fisheries Service, California Department of Fish and Wildlife, Monterey Bay National Marine Sanctuary, Esri, Moss Landing Marine Laboratories.

The EFH review process offered an opportunity for stakeholders to provide input on the boundaries of current EFH conservation areas, HAPCs, and other suggestions (e.g., research and gear options) by submitting a proposal to PFMC. As the regional fishery management council that has jurisdiction over the exclusive economic zone off Washington, Oregon, and California, PFMC recommends management measures to be implemented by NMFS. As a local stakeholder, MBNMS

was interested in engaging in the EFH review process. Other stakeholders such as trawl fishermen and nonprofit conservation organizations were also interested in engaging in the process because each entity recognized that EFH regulations are part of a valuable suite of spatial management tools. The trawl fishermen wanted more fishing opportunities whereas the conservation groups were interested in protecting more areas. MBNMS was interested in both of these goals, and thus brought together representatives of the different groups to facilitate the development of the EFH proposal. This collaboration meant that the local stakeholders most affected by the outcomes were able to participate in the review process to evaluate existing groundfish EFH regulations.

Before engaging in the EFH review process, it was up to MBNMS to determine whether areas in the Sanctuary that contained habitats important to groundfish were also vulnerable to bottom trawling. Groundfish are fish that live on or near the bottom of the ocean and include rockfish (e.g., bocaccio, cowcod, yelloweye), flatfish (e.g., petrale sole, Dover sole), roundfish (e.g., lingcod; figure 11.3), sharks, and skates. Many managed fish species are dependent on hard-substrate habitats during some portion of their life cycle. MBNMS staff analyzed available data on hard-substrate habitats, including rocky reefs, soft substrate, and biogenic habitat, in the Sanctuary. Benthic organisms attached to the substrate, such as kelp, corals, and sponges, can play an important role in increasing the structural complexity of a bottom habitat, and are therefore considered biogenic habitat. Identifying the location and presence of hard substrate, corals, and sponges was paramount because these habitats are important to groundfish. These habitats provide important physical structure and are also very sensitive to impacts from bottom trawling and are slow to recover from these impacts. Bottom trawling is a fishing technique in which a net is dragged across the seafloor to catch groundfish, but other organisms living on the seafloor, such as corals and sponges, can also be caught by the net. By analyzing new biological, geological, and human-use data in GIS, MBNMS staff were able to illustrate that there are areas within MBNMS that are important to groundfish but are also vulnerable to bottom trawling.

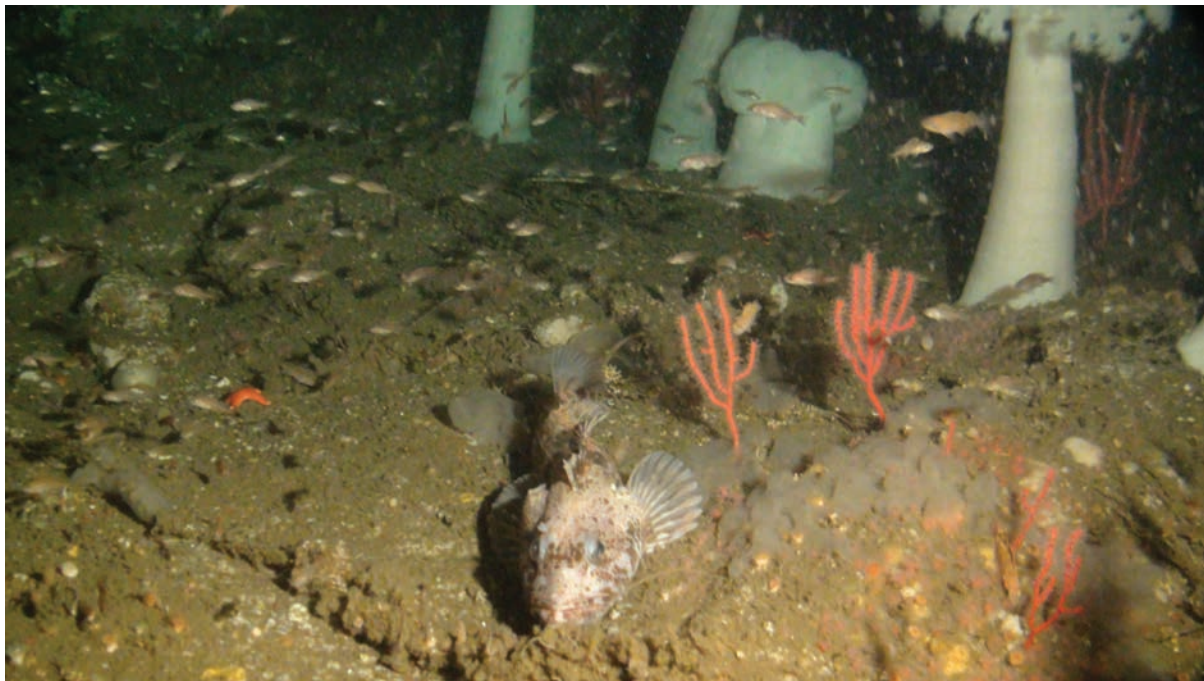


Figure 11.3. Lingcod (*Ophiodon elongatus*) and Cnidaria, including anemones and gorgonians. Courtesy of NOAA Monterey Bay National Marine Sanctuary.

As part of the EFH review process, MBNMS submitted a proposal in July 2013 to PFMC that included anticipated benefits for all three stakeholder groups: trawling, conservation, and resource management. The main goal of the collaborative proposal was to balance conservation and sustainable uses. Specifically, the proposal aimed to balance the protection of EFH for groundfish with opportunities for groundfish bottom-trawl fishing within MBNMS.

MBNMS offered several key ingredients: a venue, GIS technical support, the expertise for developing a sound and complete proposal, and mediation between the stakeholders. The success of this collaborative endeavor is owed in large part to the suite of GIS tools used, including GIS projects and products that helped inform discussions. MBNMS used GIS to provide a clear understanding of the current spatial management, distribution of sensitive resources, and distribution of historical and current fishing efforts. Using GIS interactively during the group process (e.g., quickly turning data layers on or off within an ArcGIS project that was shown on a screen to everyone in the room) proved valuable, as it enabled stakeholders to see the trade-offs of various proposals in real time. MBNMS staff not only displayed proposed boundary changes to EFH conservation areas in GIS, but also used GIS to manage discussions (e.g., switching to different areas or the whole region to enable the group to move forward, even during times of tension and disparity). GIS helped members of the stakeholder group commit to staying involved, as it helped them envision a great variety of potential future spatial management scenarios. As such, the process was not unlike similar activities elsewhere in which collaborative, participatory planning and decision-making activities among various stakeholders are guided effectively by the real-time use of GIS (e.g., Gleason et al. 2010; Lanier et al. 2011; Paul et al. 2012; Gass et al. 2013; Stelzenmuller et al. 2013).

Methods

Study Area

The proposal's study area was established solely within the federal waters (i.e., >3 nm from shore) of MBNMS south of Point Año Nuevo (see figure 11.1). State waters were excluded from the study area because trawling is currently not allowed within California's state waters, and California recently implemented a network of marine protected areas (MPAs) using an extensive stakeholder process. The study area also included the Davidson Seamount Management Zone, a noncontiguous offshore portion of MBNMS. The study area covers a total of 3,992 sq mi.

Identifying Stakeholders and Data Needs

The proposal submitted to PFMC was the product of an 11-month collaborative stakeholder process that began in August 2012 with meetings of MBNMS and fishing industry stakeholders. These stakeholders included MBNMS Advisory Council representatives (harbors and commercial fishing), the Alliance of Communities for Sustainable Fisheries, Monterey Bay trawl fishermen, and the City of Monterey, California. Meeting with fishing interests was an essential first step in the process, as it allowed MBNMS and fishing industry representatives to discuss their perspectives on the implementation of EFH processes and management. It also allowed MBNMS to understand where the historically important trawled areas were located. Last but not least, it allowed MBNMS to showcase the GIS datasets to be used in the process, especially as the fishing interests did not have GIS tools readily available. In June 2013, MBNMS invited additional stakeholders, representing conservation interests, to be part of the proposal development, as it was beneficial to all involved to discuss options for EFH modifications with all groups of interests. The conservation representatives

were from Oceana, the Natural Resources Defense Council, Ocean Conservancy, The Nature Conservancy, California Risk Pool, and Environmental Defense Fund.

In early discussions, group members recognized that the focus of the collaborative proposal would be to spatially modify EFH conservation areas by adding new areas that contained sensitive resources in need of protection from bottom-trawl fishing gear, while also reopening some areas to gain access to historically fished areas of economic importance to the bottom trawling community. This strategy was settled on because the representatives were mostly satisfied with the spatial management implementations of EFH, but they also wanted a few small changes to certain areas to maximize outcomes that they felt were important. Knowing that spatial modifications would be the focus of most of the discussions, the group had to familiarize themselves with various data, including

1. Data for benthic habitat, to identify which areas were consistent with groundfish EFH within MBNMS but were not protected by current EFH management measures. This data included habitats that are unique, rare, or ecologically sensitive, either because of geologic features or that contain known biogenic habitat (i.e., deep-sea corals and sponges), and habitats that could be vulnerable to impacts of fishing activities for groundfish managed by PFMC.
2. Data to identify where new EFH HAPCs and new conservation areas that minimize adverse fishing impacts on groundfish EFH could be proposed, and further the protection of both biogenic and physical habitat for groundfish through prohibitions on bottom trawling.
3. Data to identify areas for proposing the reopening of certain portions of existing EFH conservation areas to return valuable historical fishing grounds to the bottom trawling fleet.

Regional Data Acquisition

MBNMS GIS staff became well acquainted with the regional data and associated metadata made available through the *5-Year Review of Pacific Coast Groundfish EFH, Consolidated Geographic Information Data Catalog and Online Registry* (Pacific Coast Ocean Observing System 2014). The datasets available in the data catalog were fully documented in the *Pacific Coast Groundfish 5-Year Review of Essential Fish Habitat Report* (PFMC 2012), the EFH synthesis report (NMFS 2013b), and the appendix to the EFH synthesis report (NMFS 2013a). The data portal allowed for easy downloading of data and maps of known physical habitats of the US West Coast, trawling efforts, the presence of biogenic species, groundfish occurrence models, MPAs, and nonfishing pressures. MBNMS GIS staff delivered presentations to other MBNMS staff and stakeholders to showcase the most relevant regional data for the collaborative proposal within the MBNMS study area, and to convey important caveats regarding how the datasets were collected, portrayed, and analyzed.

MBNMS staff integrated the relevant regional data into a desktop GIS project to use during the stakeholder meetings. The stakeholder group used data layers largely provided by the National Oceanic and Atmospheric Administration (NOAA) Deep Sea Coral Research and Technology Program (DSCRTP), which indicated the locations in which sponges, corals, and pennatulids (sea pens) have been observed in situ or collected in NMFS's bottom-trawl surveys. These datasets helped all members of the group understand where biogenic habitat was located when stakeholders discussed boundary changes during stakeholder meetings. Additionally, bathymetry, physical habitat, and current spatial management layers were always useful during discussions. MBNMS staff also incorporated the occurrence models for six groundfish species chosen to represent the suite of groundfish on the US West Coast as modeled by the NOAA Northwest Fisheries Science Center (NWFSC) and NOAA National Centers for Coastal Ocean Science (NCCOS). The models were based on NMFS bottom-trawl surveys and some in situ observations.

Local Data Acquisition

The regional datasets provided by NMFS spanned the entire US West Coast, so MBNMS GIS staff augmented them with local data from the Monterey Bay Aquarium Research Institute (MBARI) and California State University, Monterey Bay (CSUMB). Both institutions have developed databases using in situ observations of fish and invertebrates, which MBNMS staff used to corroborate the NMFS and NCCOS models and better understand groundfish distributions.

MBARI used high-resolution video equipment to record observations of the marine environment during more than 300 remotely operated vehicle (ROV) dives per year. In MBARI's 25 years of ROV operations (1989 to the present), over 16,000 hours of videotapes have been archived, annotated, and maintained as a centralized institutional resource. This video library contains detailed footage of the biological, chemical, geological, and physical aspects of the Monterey Bay submarine canyon and other areas of the US West Coast. MBARI has developed the Video Annotation and Reference System (VARS), which consists of software and hardware, to facilitate the creation, storage, and retrieval of video annotation records from the ROV dive tapes. The public can run queries on VARS, but the most recent data is embargoed for two years to allow MBARI scientists the first opportunity to publish findings using the ROV data. The groundfish query results used for the collaborative proposal were run internally by MBARI staff, and thus include the most recent data.

The MBARI VARS query was run for 10 species and one complex (table 11.1). Species selection was based on the groundfish species modeled by both NMFS and NCCOS and the additional species modeled only by NCCOS (NMFS 2013a, 2013b). Each query was exported as a text file, and then imported to Microsoft Excel, where headings were modified for better compatibility with ArcGIS software. The files were converted to an Esri shapefile, and hyperlinks to images were activated.

Table 11.1. Local Database Queries for Select Groundfish and Sessile Invertebrates

Common Name	Scientific Name	MBARI VARS Query	CSUMB Query
Dark blotched rockfish	<i>Sebastes crameri</i>	x	None in database
Yelloweye rockfish	<i>Sebastes ruberrimus</i>	x	x
Sablefish	<i>Anoplopoma fimbria</i>	x	x
Shortspine thornyhead	<i>Sebastolobus alascanus</i>	x	None identified to species yet
Longspine thornyhead	<i>Sebastolobus altivelis</i>	x	None identified to species yet
Thornyhead complex	<i>Sebastolobus complex</i>		None in MBNMS EFH proposed areas
Greenstriped rockfish	<i>Sebastes elongatus</i>	x	x
Petrale sole	<i>Eopsetta jordani</i>	x	x
Dover sole	<i>Microstomus pacificus</i>	x	x
Lingcod	<i>Ophiodon elongatus</i>	x	x
Pacific ocean perch	<i>Sebastes alascanus</i>	None in database	None in database
Chilipepper rockfish	<i>Sebastes goodei</i>	x	x
Bocaccio	<i>Sebastes paucispinis</i>	Not run	x
Pacific halibut	<i>Hippoglossus stenolepis</i>	Not run	x
Canary/Vermillion/ Yelloweye rockfish complex		Not run	x
Canary rockfish	<i>Sebastes pinniger</i>	Not run	x
Young of the Year (YOY) rockfish		Not run	x
Widow rockfish	<i>Sebastes entomelas</i>	Not run	None identified to species yet
Corals		Included in DSCRTP Database	x
Sea pens and sea whips		Included in DSCRTP Database	x
Sponges (>10 cm)		Included in DSCRTP Database	x

Note: x is records returned from the query.

A similar process was used to query the CSUMB database for demersal fish and invertebrate species of interest. CSUMB staff built a Microsoft Access database that contains habitat and fauna observational data from approximately 45 hours of ROV video and 150 hours of towed camera sled video collected in MBNMS. ROV datasets were from 2009, 2010, and 2012. The towed camera sled datasets were from 2007 to 2011. Additional video was taken from the camera sled in 2006, but those datasets were analyzed separately for the EFH proposal and are not yet in the database. Organisms were identified to the lowest taxonomic level possible, which in many cases was only

to genus or species complex rather than species. This result was because of many factors, including visibility at depth, vehicle lighting, and organism position relative to the video camera. Database query results included the organism or complex of interest, count, and associated latitude and longitude coordinates. Each query was exported as a Microsoft Excel file and converted to an Esri shapefile. CSUMB database queries were run for invertebrates in addition to fish (see table 11.1). CSUMB's invertebrate datasets were not included in the regional DSC RTP database available on the EFH catalog, so those CSUMB queries helped augment the in situ data from DSC RTP.

Finally, the proposal was enhanced by local knowledge and information from fishermen. This anecdotal information was of a larger cartographic scale than the trawling effort data that was provided in the EFH data catalog. Because of the confidentiality of fishing effort data, only areas fished by three or more vessels can be made public through the EFH data catalog. However, by working with the trawl fishermen, MBNMS staff were able to understand which local areas were important to each individual fisherman. MBNMS GIS staff helped the fishermen capture these areas within GIS so that their datasets were available in the same medium as the biological, geological, and management data. During the first few meetings, MBNMS GIS staff digitized their areas of interest in a live editing session using ArcGIS 10.1 for Desktop software (figure 11.4). The trawl fishermen provided site-specific socioeconomic information on the locations of historically productive bottom-trawl fishing grounds that were then captured as attributes in GIS. Trawl fishermen also informed MBNMS staff and other stakeholders about the operational logistics that aid in an economically viable bottom-trawl fishery within the study area. These datasets provided vital information that helped the stakeholder group develop a collaborative proposal.

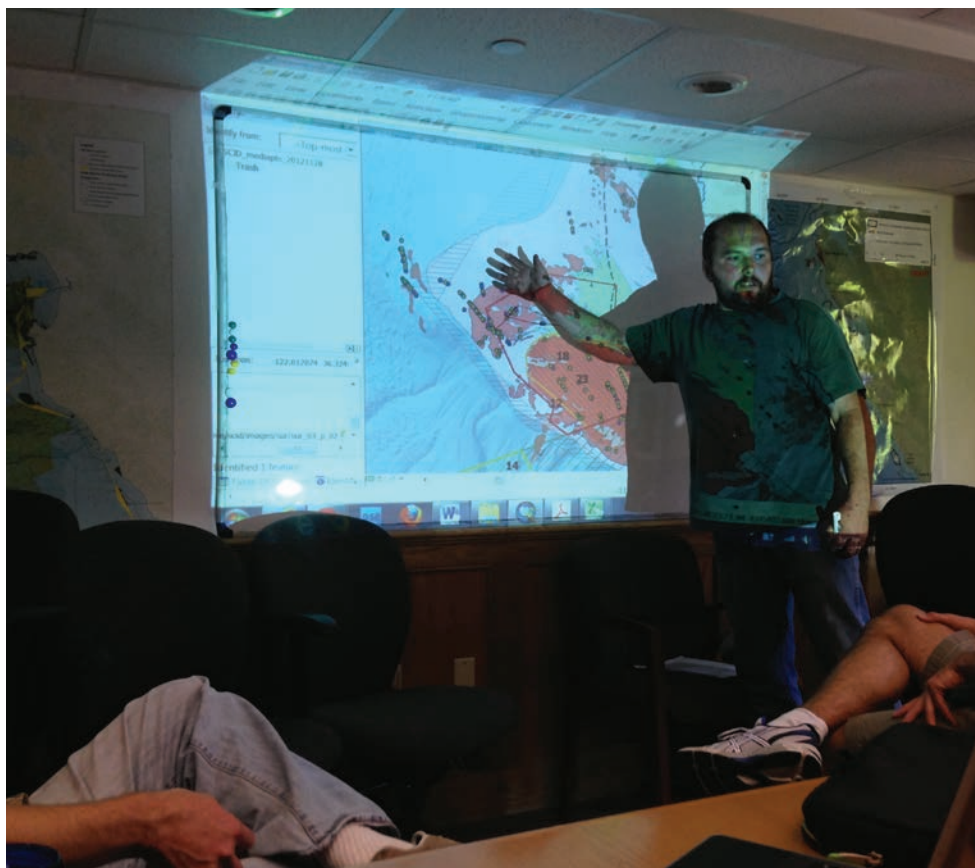


Figure 11.4. Trawl fisherman points to an area on an ArcGIS for Desktop map projected on a screen, which enabled MBNMS staff to capture spatial comments. Courtesy of NOAA Monterey Bay National Marine Sanctuary.

GIS Tools

Relevant US West Coast and local data was compiled into an ArcGIS Online web map (see a link to the EFH Story Map in the “Supplemental Resources” section at the end of this chapter). The datasets that were referred to most often, aside from the base layers that oriented the user, were the biogenic habitat data layers and associated image links. Whenever possible and appropriate, MBNMS GIS staff converted regional US West Coast raster datasets to vector form and clipped them to the study area (as vector files use fewer service credits). The ArcGIS Online web map allowed all staff and stakeholders to explore the dataset and develop strategic input for meetings based on these datasets. The nontechnical staff of MBNMS also used the ArcGIS Online service while writing the introduction and discussion sections of the proposal. ArcGIS Online allowed them to quickly access biological and geological characteristics of each individual area and select ROV-captured images to include in the proposal to best illustrate the habitats of these areas.

In addition, an Esri Map Book app was developed for individual areas using data-driven pages to showcase the biogenic, management, bathymetric, and geological data for each area. The Data Driven Pages toolbar was enabled, and the EFH boundary modification layer proposed for MBNMS was selected as the index layer. The map book was an asset because it provided a quick reference to larger-scale maps of each of the proposal areas, which focused on the locations of biogenic habitat from regional and local sources.

Calculations

The EFH modification polygons in the proposal were developed using an iterative process, which required constant modification and refinement in GIS on the fly during the numerous meetings with stakeholders. The MBNMS GIS team also provided summary statistics for each boundary iteration. ArcGIS 10.1 for Desktop was used in all GIS processes, often with the ArcGIS Spatial Analyst extension. MBNMS developed a matrix in Microsoft Excel to store important information (e.g., total area of various substrate types, number of corals seen in situ), most of it calculated using GIS, for each of the modified polygon iterations, making it easy to compare and contrast the data. The most relevant data was transferred from the matrix to the attribute tables of the polygons in both the ArcGIS desktop and online projects.

MBNMS GIS staff added a variety of useful habitat data as attributes. For example, staff used the ArcToolbox function Zonal Statistics as Table (Spatial Analyst extension) to summarize raster values of depth and percent slope by each depth zone (continental shelf: 30–100 m; continental shelf break: 100–300 m; continental slope 1: 300–800 m; continental slope 2: 800–3,000 m) for each of the proposed areas. This tool summarizes the values of a raster within the zones of another raster or feature layer and reports the results to a table. The summary attributes include the mean, min, max, median, and standard deviation of the values of the raster grids per zonal area. Other important attributes summarized include physical habitat type (hard or soft) and whether an area was classified as being in a canyon. Areas were then calculated in ArcGIS using the Calculate Geometry tool. The resulting shapefile was exported as a Microsoft Excel table, and a variety of pivot tables were generated so the data could be analyzed from different perspectives.

Within Excel, the Shannon-Wiener diversity index, H' (Shannon 1948), was calculated as a way to examine habitat diversity within each proposed area. There were 11 possible habitat classes, which combined the depth zone, substrate type, and canyon habitat. Higher diversity values indicated a balanced proportion of habitat classes.

Results

The final proposal contains 10 areas to add to EFH conservation areas and 5 areas to reopen (figure 11.5). The proposal considered these modifications as a comprehensive package that will minimize, to the extent practicable, the adverse effects of bottom-trawl gear on groundfish EFH within the study area. In-depth and overview GIS analyses of the individual areas and the whole package were incorporated in the proposal. For example, the proposal adds 260 sq mi to EFH conservation areas, of which 84% is thought to be soft and 16% is hard bottom. In addition, 153 sq mi, almost all of which is estimated to be soft bottom, is proposed to be reopened to bottom trawling.

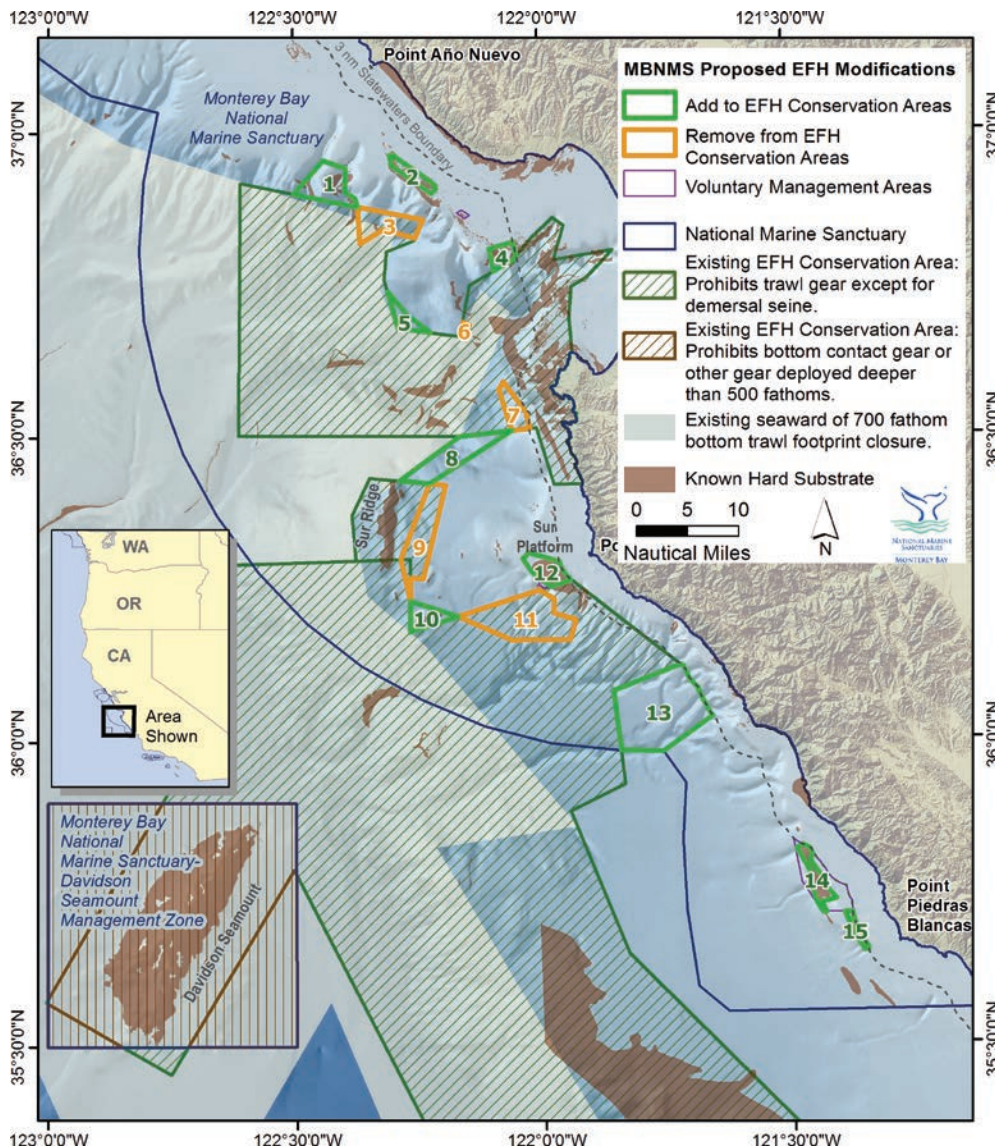


Figure 11.5. Essential fish habitat (EFH) conservation area modifications within the Monterey Bay National Marine Sanctuary (MBNMS) study area as proposed by the collaborative proposal. Modifications include adding (in green) or removing (in orange) areas from the existing conservation areas. Courtesy of NOAA

Monterey Bay National Marine Sanctuary. Data from NOAA National Marine Fisheries Service, California Department of Fish and Wildlife, Monterey Bay National Marine Sanctuary, Esri, Moss Landing Marine Laboratories.

Because MBNMS GIS staff integrated a variety of layers in both the ArcGIS for Desktop project and ArcGIS Online web map, it was possible to use seafloor imagery to validate substrate data. One such example pertained to Area 12 at Point Sur Platform, where the habitat layer obtained from the EFH data catalog delineated a smaller area of the platform as hard substrate compared with two independent sources of substrate data provided by the US Geological Survey (USGS) and CSUMB. This area proved to be vital hard-substrate habitat and led us to proposing Area 12 as an additional EFH conservation area.

Many maps were included in the proposal to illustrate the spatial relationships between various data. Figure 11.6 is a map book example page and showcases biogenic data in Area 12 and the lack thereof in Area 11, Sur Canyon, which was an area that fishermen wanted to reopen to trawling for deep continental slope fishes. This map shows the biogenic data (e.g., sponges) from the DSCRTP and CSUMB databases. Area 12 is an area that is a proposed addition to EFH conservation areas. As an additional map portfolio example, MBNMS GIS staff combined the NMFS groundfish occurrence models with the local in situ observations of those groundfish, and then overlaid the proposed EFH conservation area boundaries to have a better understanding of the local applicability of the models, in addition to which species were captured within the proposed boundaries. For example, figure 11.7 shows the NMFS modeled data for longspine thornyhead occurrence overlaid by MBARI observations and effort data. The model clearly captures the longspine thornyhead preference for soft continental slope habitats. MBARI in situ observations and effort data suggest that many fish are also found in slightly shallower waters than the model predicts.

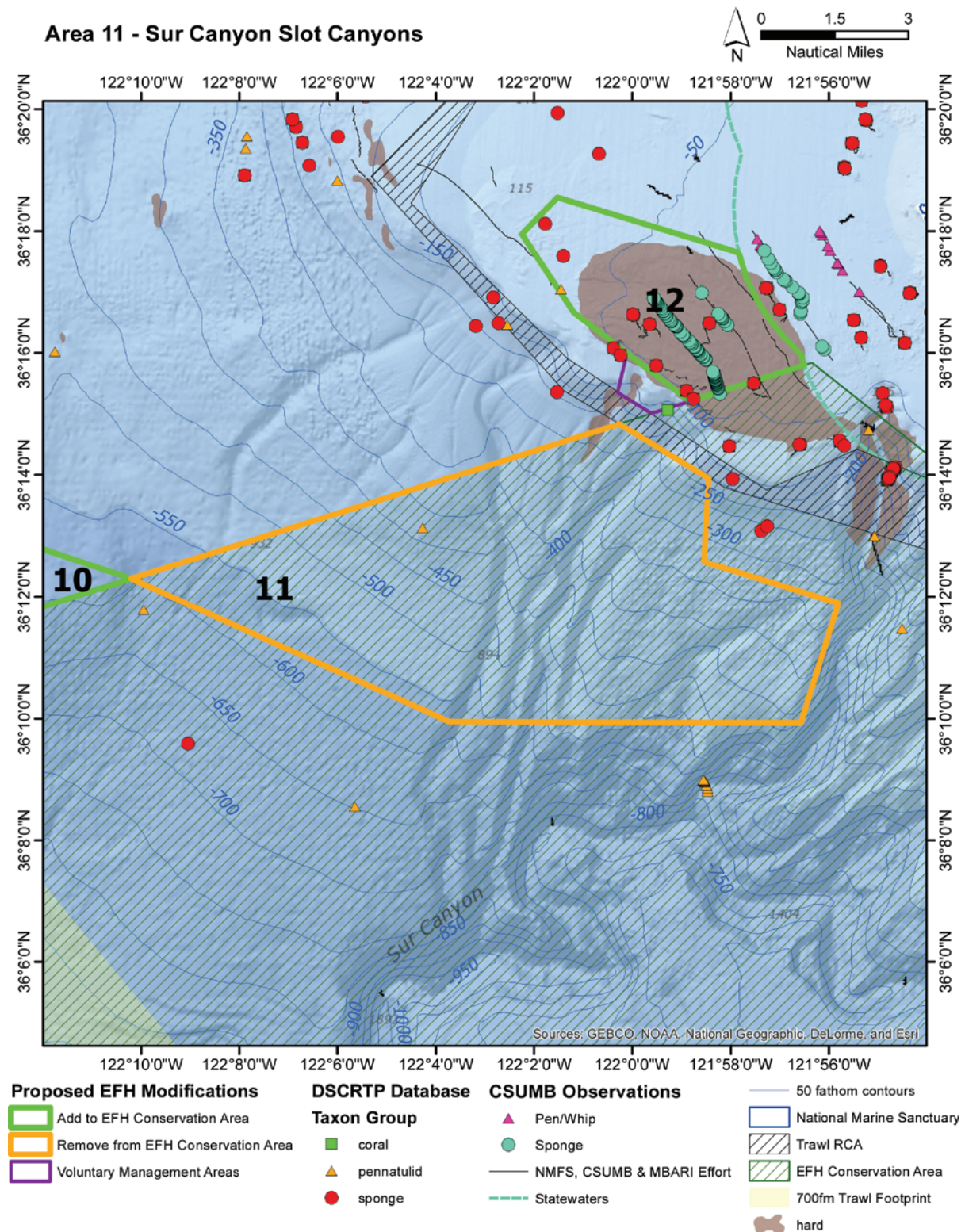


Figure 11.6. Map book example page portrays biogenic data such as observations of corals and sponges and proposed essential fish habitat conservation area modifications, including Areas 11 and 12. Courtesy of NOAA Monterey Bay National Marine Sanctuary. Data from NOAA National Marine Fisheries Service, GEBCO, National Geographic, DeLorme, and Esri.

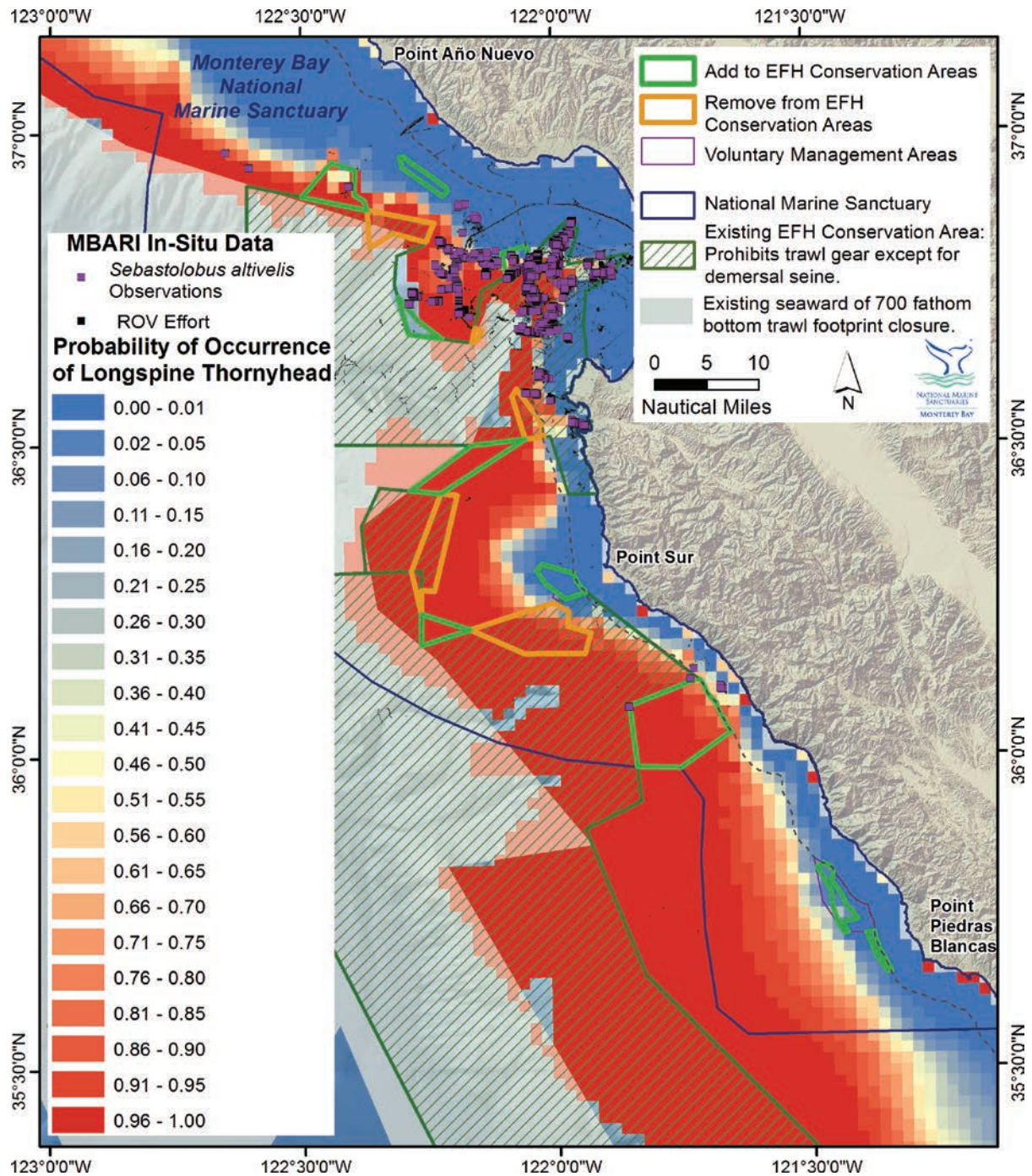


Figure 11.7. National Marine Fisheries Service occurrence model for longspine thornyhead (*Sebastolobus altivelis*) and in situ observations by Monterey Bay Aquarium Research Institute (MBARI) within the Monterey Bay National Marine Sanctuary study area. The red area covers the continental slope and symbolizes high probability of occurrence. Courtesy of NOAA Monterey Bay National Marine Sanctuary. Data from NOAA National Marine Fisheries Service, Monterey Bay Aquarium Research Institute, California Department of Fish and Wildlife, and Esri.

Conclusion

All participating stakeholders were dedicated to crafting a collaborative proposal that balanced protection of groundfish essential fish habitat with allowing for bottom trawling opportunities. Engaging in this collaborative process was an important step in building a persistent cooperative relationship and trust between MBNMS, fishermen, and the conservation community. Using GIS as a main decision support tool allowed the collaborations to stay on track as it allowed stakeholders to have a shared understanding of the spatial distribution of resources and fishing efforts. By using live GIS maps, a wayward discussion could be refocused to a specific place to enable the group to move forward, or data layers could be added in real time to help the group see trade-offs between the proposed changes in the EFH conservation area boundaries. At the time of this writing, the proposal was still under consideration by PFMC for implementation.

The EFH data catalog provided streamlined access to data layers and associated information to all levels of GIS users. The GIS desktop user was able to download zipped map packages that contained thorough metadata. The online user could access the data via ArcGIS Explorer software, ArcGIS Online, Google Earth, or the Pacific Coast Ocean Observing System (PaCOOS) map viewer (Goldfinger and Romsos 2014). The non-GIS user was able to download prepared maps. The data catalog was a crucial support tool for developing the proposal by providing a range of data (e.g., biological, anthropogenic, and habitat) to a variety of users. However, augmenting the regional data with local data proved useful and insightful. MBNMS GIS staff also had copies of some of the regional data within the same GIS project so that the data could be symbolized based on local scale ranges, which were often not as extensive as the US West Coast ranges. This helped us better understand the local variability of the data. GIS staff were also well versed in the associated caveats of all the data so that it could be used appropriately. The collaborative proposal showcases the benefits of pairing together stakeholders having different interests and knowledge with GIS staff who were intimately familiar with the data caveats and limitations.

ArcGIS Online can be a valuable tool for stakeholder processes as it helped us reach consensus among stakeholders. It is user-friendly for nontechnical staff and stakeholders and is also a useful asset to those versed in GIS. MBNMS GIS support staff selected a finite number of layers for the ArcGIS Online project so as not to overwhelm users because there was a tremendous amount of spatial data associated with this project (see the EFH Story Map link in the “Supplemental Resources” section at the end of this chapter). GIS staff also ensured that links functioned properly, attributes and attribute names were fully expounded, and images and descriptive graphs for each feature were included. It required time and dedication by the GIS staff but proved to be an essential ingredient in the collaborative process.

MBNMS managers noted that the main reason the collaborative process was effective was because of the use of a full suite of GIS products. Figure 11.8 captures that truth as a conservation group and the trawling fleet are surrounded by various spatial products as they discuss the issues. First, they discuss an area projected on screen from a geoenabled PDF file. A large printed poster map of the study area is on the wall behind the trawl fleet representative. In addition, a computer running ArcGIS for Desktop is in the foreground. Using desktop GIS allowed MBNMS GIS staff to digitize and analyze areas in real time, which proved informative for the group in evaluating all options. Running live ArcGIS during the meetings allowed stakeholders to ask and respond to questions efficiently, which allowed for much greater progress than without real-time spatial data.

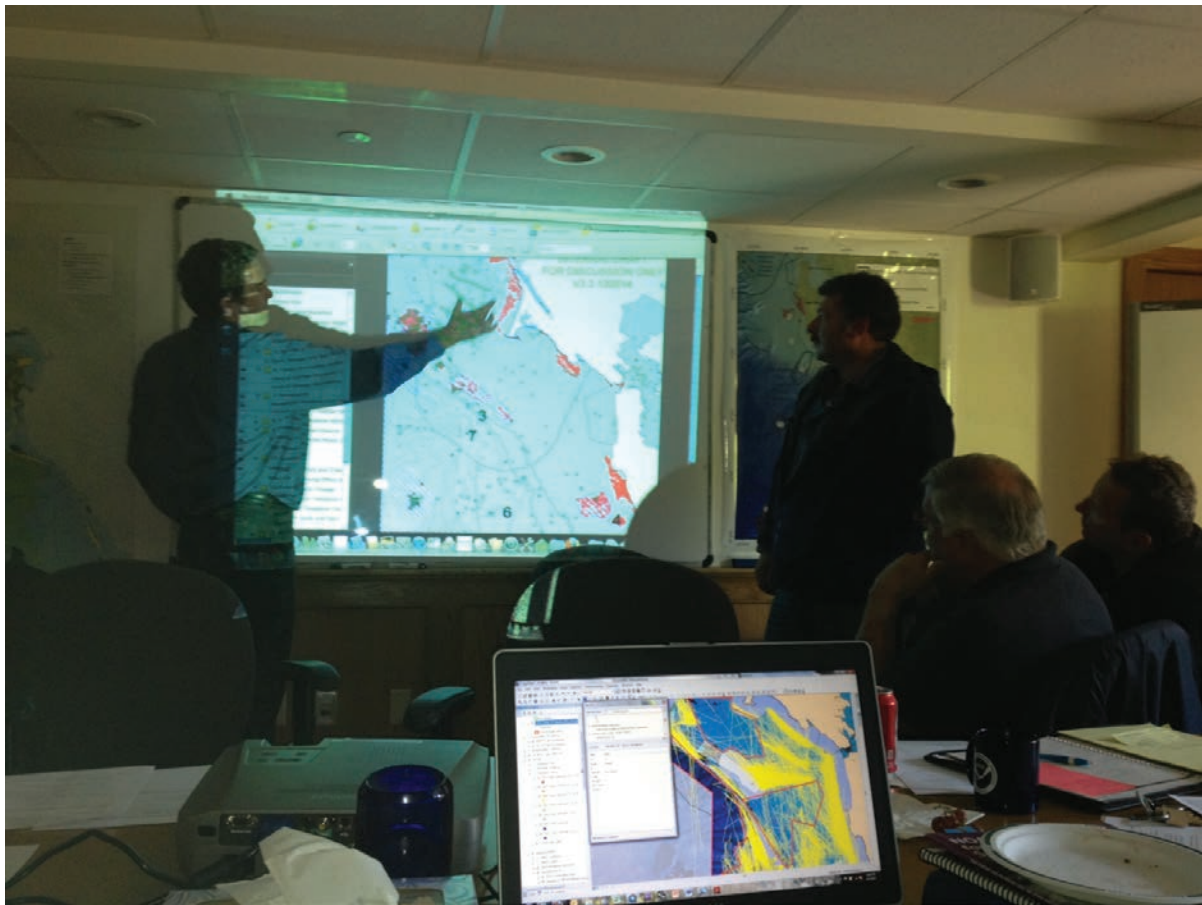


Figure 11.8. Representatives from a conservation group (left) and trawling fleet (right) discuss their ideas while reviewing a geoenabled PDF as other stakeholders listen and study the projected map using ArcGIS for Desktop software. Courtesy of NOAA Monterey Bay National Marine Sanctuary.

The proposed boundary modifications of Areas 1–15 (see figure 11.5) represent a package of areas that, if taken collectively, provide increased protection to rocky reef HAPCs. It is useful to include these additional hard-substrate areas in the package along with sensitive biogenic species, including corals and sponges, while also providing increased access to valuable fishing grounds. The package comprises 10 additions to EFH conservation areas that prohibit bottom-trawl gear and 5 modifications that reopen portions of current EFH conservation areas to bottom trawling. A total of 106 sq mi was added to EFH conservation areas within the MBNMS study area, and of that total increase, 39% is hard substrate. In the end, the stakeholders were able to agree on both areas to reopen and areas to close to trawling, and deliver a collaborative proposal to PFMC for Areas 1–13, again still under consideration. Two of the areas in MBNMS, Areas 14 and 15, were negotiated without the participation of Oceana, Ocean Conservancy, or the Natural Resources Defense Council. At the end of the stakeholder process, MBNMS finalized the design of these two areas with the California Risk Pool, as the full group did not have the time or opportunity to reach consensus on these areas.

In addition, the proposal identifies and proposes three “voluntary management areas” (see figure 11.5) that will not be affected by EFH regulation, yet will be recognized as areas to be avoided by trawlers because of sensitive habitat. The details on how long the voluntary measures will be in place, and the time scale for revisiting the agreement, were still under consideration. These areas are nonregulatory, will be managed and monitored by MBNMS, and can be considered as experimental

or pilot areas to test the effectiveness of the concept of voluntary management areas for habitat protection.

In summary, the array of proposed modifications to EFH conservation areas can demonstrate a net benthic habitat benefit to groundfish EFH by

- further minimizing adverse impacts of bottom-trawl fishing to groundfish EFH to the extent practicable, based on new and newly available information;
- providing socioeconomic benefits on both the fishery and community scale;
- increasing access of bottom-trawl fishing activity to historically productive trawl fishing grounds in MBNMS that currently prohibit bottom-trawl activity while minimizing adverse impacts to EFH groundfish as a whole (the reopening comes in the context of an overall package of revisions that will yield a strong net increase in habitat protection); and
- increasing the overall protection of hard substrate, including rocky reef HAPCs, biogenic habitats (e.g., corals and sponges), canyon habitat, and soft-substrate habitat, at various depths.

One measure of the success of this collaborative effort is that the proposal received eight support letters from a variety of interests. The support letters were not just from the stakeholders that had representatives engaged in the collaborative proposal, but also from other influential entities, including Julie Packard of the Monterey Bay Aquarium, Mark Stone of the California state Legislature, and US Congressman Sam Farr, representing California's Central Coast (see sidebar).

***Letter of US Rep. Sam Farr (D-CA) to NMFS and PPMC,
October 21, 2013***

Habitat protection, based on sound science and active stakeholder and community participation, is a fundamental management tool that the Council is authorized to employ as it works to restore and sustainably manage our nation's fish populations. The Monterey Bay National Marine Sanctuary is one of the prized gems of our ocean. NOAA is authorized to protect and provide for multiple uses of the resources within the Sanctuary. To do so, they must continue to facilitate similar negotiations, bringing stakeholders to the table to work collaboratively from the beginning. This will not only foster trust and understanding between all parties, but also provide a forum to make the hard decisions about how to protect and use the most valued areas in our ocean.

In my view, habitat protection is a critical tool of fishery management, and we must encourage all stakeholders to review the best science, work collaboratively to build trust, and identify areas for protection that will help us sustainably protect and manage our fish populations. I call on the Council to endorse the outcome of the Sanctuary-facilitated negotiation, thereby empowering the Sanctuary staff, local officials, fishermen, and NGOs to continue the challenging work by returning to the negotiating table. There is much more work they must do together.

As Congressman Farr notes in his letter of support (see sidebar), there is much more that the stakeholder group must do together to achieve other resource protection and use goals. Also, in the event that the proposal does not go through PPMC's implementation process, the stakeholder group can still work together to identify other potential alternative resource management opportunities to

achieve similar goals to those of the collaborative proposal. The group found the multitude of GIS tools used during this proposal development process to be useful and reliable. As such, a similar stakeholder decision-making process can be used to consider alternative management applications, such as implementing other voluntary management areas. The spatial data provided a common language for stakeholders during the development of this proposal and will be a keystone to future collaborations. The development of this proposal, with the aid of various types of GIS tools, provides a strong foundation for fishermen, conservationists, and resource managers to work collaboratively toward other resource management goals in the future.

Acknowledgments

We thank our various collaborators at MBARI and CSUMB, as well as the various stakeholders from the commercial trawling, conservation, and resource management communities who worked with us on the EFH proposal. We are also grateful to PFMC and NOAA NMFS for their guidance and support. The editorial assistance of Dawn J. Wright, and the comments and suggestions of two anonymous reviewers, greatly improved this chapter.

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Supplemental Resources

Dawn J. Wright, ed.; 2016; *Ocean Solutions, Earth Solutions*, second edition; http://dx.doi.org/10.17128/9781589484603_11d

For the digital content that goes with this chapter, go to the following link or QR code. A hyperlink is also available in the book's online resources (esri.com/esripress-research/ocean-solutions-2e).

- Story Map app for essential fish habitat (EFH), at <http://bit.ly/1a6yzqX>



CHAPTER 12

More Than Maps: Connecting Aquarium Guests to Global Stories

Jennifer Lentz, Emily Yam, Alie LeBeau, and David Bader

Abstract

With a mission to instill a sense of wonder, respect, and stewardship for the Pacific Ocean, its inhabitants, and ecosystems, the Aquarium of the Pacific in Long Beach, California, aims to connect its diverse audience of 1.5 million annual visitors to beautiful animal collections, conservation messages, and ideas that inspire a better understanding of human relationships to environments and a changing global ecosystem. To promote exploration of complex issues such as climate change, ocean exploration, ocean acidification, extreme weather, and how global data is collected, the Aquarium makes use of various technologies and communication messages. Tools such as digital “interactives,” spherical projections of global visualizations, large-scale maps, geospatial products and apps, and ArcGIS software provide Aquarium guests context, visualizations, and time to explore the things that are necessary to constructing an understanding of global systems and relationships between the pieces.

Although these innovative technologies are enticing and hold the attention of the audience, they are most effective when paired with skilled educators who ask questions and guide guests to make their own discoveries. As an Informal Science Education Institution, the Aquarium provides experience and exposure to its guests who may not have previously experienced these underwater worlds, or heard the stories from a global perspective. These experiences provide the basis for understanding, appreciating, and taking action to effect change in the future. By connecting people to science, and as the trusted conveyer of current information, the Aquarium is helping to create a more scientifically literate community.

As the Aquarium moves forward with its programs and initiatives, it will continue to strive to be “more than a fish tank” as it creates innovative, immersive experiences that make use of geospatial technologies to serve students, teachers, families, and adult audiences while inspiring an appreciation for the impact that humans have on our planet and on the future that we can create together.

Introduction

The Aquarium of the Pacific

The Aquarium of the Pacific is a public, nonprofit 501(c)(3) organization, located along Rainbow Harbor, in downtown Long Beach, California. Since opening its doors in 1998, the mission-based facility has aimed to instill a sense of wonder, respect, and stewardship for the Pacific Ocean, its inhabitants, and its ecosystems. This mission is carried out by providing engaging, entertaining, educational, and empowering exhibits and programs about the Pacific Ocean and the people who interact with it, live near it, and depend on it for food, recreation, and inspiration. The Aquarium is an Association of Zoos and Aquariums (AZA) accredited institution that serves approximately 1.5 million annual visitors, making it the fourth-most attended aquarium in the nation in 2014. According to a national marketing survey, the Aquarium serves the most ethnically diverse audience of any major aquarium (Morey Group 2014).

The Aquarium of the Pacific is home to more than 12,000 animals that represent a range of habitats, including local, temperate Southern California waters; cool northern Pacific environments; tropical western Pacific islands; and the darkness of the deep sea. Guests who visit the Aquarium can touch sharks, sea jellies, and tide pool animals; stroll through an aviary of colorful lorikeet birds; watch a training enrichment session with sea otters; and walk through a tunnel into the Tropical Pacific habitat. Going beyond its live animal collection, the Aquarium of the Pacific prides itself on using experts in various fields of ocean science to develop programs that are then communicated through the Aquarium of the Pacific's educators, exhibits, and use of cutting-edge technologies. Ocean exploration, global climate change, ocean acidification, overfishing, and medicines from the sea are just a few of the topics that are explored through the Aquarium's exhibits, films, and programs.

Complementing the animals, a broad portfolio of technologies is used to deepen the learning experience at the Aquarium. Guests explore near real-time, historical, and modeled data projected on the Aquarium's Science on a Sphere (SOS) installation in the Aquarium's Ocean Science Center. Developed by the National Oceanic and Atmospheric Administration (NOAA), SOS is a 6 ft diameter sphere designed to display dynamic information on large spatial and temporal scales (McDougall et al. 2007; Randol et al. 2012). Here, guests can watch beautifully produced films and engage in discussions with educators about earth systems science, global events in weather, and climate change. A cross-site, summative evaluation of facilities using SOS technology (Goldman et al. 2010) indicates that facilitation through Science on a Sphere correlates with increased perception by learners of the value of the earth as well as a need to protect it. Results from a front-end research report on SOS interpreters at science museums show that there are challenges involved with SOS-related ongoing learning, especially with time and effort investments despite an interest from both managers and interpreters to stay up to date on information (Hart and Hayward 2011). Educator-facilitated experiences using this technology give learners the tools to interpret scientific visualizations and opportunities to connect science and data to their daily lives (Randol et al. 2012). The Ocean Exploration Hub features Hiperwall technology, a large array of flat screens that act as a portal into the world of exploration. Throughout the day, Aquarium guests can see a live feed of activities on ocean-going research vessels, including seafloor mapping, instrument deployment, and a robot's-eye view of the ocean depths as scientists search for specimens. At scheduled show times, the Aquarium broadcasts live interactions at the Ocean Exploration Hub, facilitated by educators, which allows Aquarium guests in Long Beach to interact in real time with scientists working around

the world. The Aquarium has partnered with Cisco Systems to install 15 monitors throughout the Aquarium, adding a timely dimension to the timeless dimension for which aquariums are well known.

Technology is a central element in the Aquarium of the Pacific's redefinition of the modern aquarium. Pacific Visions, the Aquarium's expansion set to open in 2017, includes a two-story, dynamic digital theater, with a 32 ft tall, 180° arc digital projection wall and a 30 ft diameter floor projection disk, which will immerse guests in a virtual ocean environment. An innovative partnership model in collaboration with leading scientists, educators, filmmakers, and artists has brought to life powerful stories to be featured in Pacific Visions, highlighting the great ocean animal migrations, the leading role of the ocean in the world's weather and climate, and the vast and undiscovered biodiversity of the ocean. Through interactive geospatial technology, guests are guiding the exploration of potential future scenarios. Once these scenarios are developed, guests will be challenged to identify the actions that citizens must take for a sustainable future. Importantly, these experiences will be accessible to educators, scientists, and the general public through digital platforms to allow for conversations, learning, and engagement to continue beyond the Aquarium visit. Technology is essential in enhancing a guest's experience at facilities such as the Aquarium because it allows for learning opportunities that are longer lasting, more powerful, and more accessible.

The Role of Informal Science Education Institutions

Informal Science Education Institutions (ISEIs) such as aquariums, museums, science centers, and zoos serve a critical role in today's society in improving public understanding of science (McDougall et al. 2007; Falk and Dierking 2010) and educating the public about conservation. ISEIs have the unique distinction of offering free-choice, learner-centered experiences that can change learning opportunities for people of all ages (Tran 2008; National Research Council 2009; Falk and Dierking 2010), promoting lifelong, life-wide, and life-deep learning. The Aquarium takes pride in its role as a supporter of traditional schools, or formal education, and strives to engage and inspire its guests and the next generation of scientists (Randol et al. 2012).

In free-choice learning environments, learners are more likely not only to absorb the information that is being presented, but also continue to seek out information on their own (National Research Council 2009). Learners who see science as fun are more likely to excel in informal science education settings (Jolly et al. 2004; Falk and Dierking 2010). Additionally, ISEIs are generally viewed by the public as a trusted and reliable source of scientific information (Falk et al. 2007; McDougall et al. 2007; Falk and Dierking 2010), with recent studies showing that the public looks to zoos, aquariums, and museums for information and guidance on environmental and conservation issues (The Ocean Project 2009a, 2009b; Centers for Ocean Sciences Education Excellence 2014). This tutelage is especially important when it comes to helping the public understand climate change (The Ocean Project 2009a).

Aquariums are particularly well suited to tell climate change and conservation stories because their live animal collections establish interest and undeniable emotional connections between people, animals, and environments (Falk et al. 2007). An aquarium visitor who enjoys the penguin or sea otter exhibits is more likely to find out about the threats that affect these animals and their habitats. Additionally, the public's trust in ISEIs as a source of information gives aquariums the power to increase not only science literacy, but also the public's awareness, understanding, and acceptance of

such issues as anthropogenic climate change. It can ultimately inspire more responsible, conservation-minded ways of living (Coyle 2005; Falk et al. 2007; McDougall et al. 2007; Randol et al. 2012).

In an era that is dominated by information and technology, the use of such media is expected to support science learning, especially in spaces such as museums, zoos, and aquariums (Coyle 2005; McDougall et al. 2007). Technology, in particular, is an important mode of learning because it allows learners to engage in inquiry that is specific to the content (Linn et al. 2004). Ucko and Ellenbogen (2008) suggest that “technology-based tools can supplement and assist, but do not necessarily have to replace, direct experiences in a museum. Rather, they make objects and phenomenon a central component of an inquiry, and then can further support learners as they extend their investigations beyond simply reading exhibit labels or even beyond a one-time visit.” Learners who interact with technology at the Aquarium are able to examine issues that are important to them, and explore these issues through conversations with educators (Randol et al. 2012). This interaction is of particular importance when an understanding of large spatial and temporal scales is necessary for learning about the complexities of global phenomena such as the scales used in climate, marine, and earth system sciences. Technology allows a facilitator to access previous learning and guide current learning because content can be reviewed and rescaled as needed (Goldman et al. 2010). Geospatial technologies lend themselves well to this kind of knowledge building because they provide a specific context for learners and can be tied directly to displays such as live animal exhibits (Barstow and Hoffman 2007; Goldman et al. 2010).

Learning Theory and Next-Generation Science Standards

Using technology as a tool, the Aquarium of the Pacific uses best practices in learning theory and pedagogy to create a rich experience for learners. Inquiry-based methods in free-choice environments allow guests to build their own sense of understanding and meaning-making. Also called *constructivism*, these learning experiences are an active process in which open-ended questions, the manipulation of objects, and real-world experiences help guide learners on their individual journey to understand the world around them (Dewey 1938; Vygotsky 1986; Jonassen et al. 1999; Markham et al. 2003; Tran 2011). “Constructivist learning environments employing inquiry-based, student-led investigations; open-ended questions; and real-world experiences are increasingly seen as a key to educational reform (Jonassen et al. 1999; Markham et al. 2003),” according to Henry and Semple (2012). Although this foundational learning theory has been evolving for over half a century, it has been translated most recently in the development and nationwide implementation of the Next Generation Science Standards (NGSS) (Quinn et al. 2012; NGSS 2014).

ISEIs, including the Aquarium of the Pacific, are positioned to support the adoption of NGSS in formal or traditional classroom environments by designing experiences that are inquiry driven, data driven, and authentic (McDougall et al. 2007; Randol et al. 2012). The Aquarium has recently revitalized its inquiry approach with the ultimate goal of creating experiences that make its learners feel and behave like explorers. Aquarium educators create opportunities for all guests to ask questions; make observations; examine scale in time and space; and discuss, debate, and share ideas. Facilitation of all public presentations, school programs, and one-on-one interpretation is now focused on four main themes that mirror the learning cycle: wonder, explore, discover, and learn (WEDL). The focus on WEDL enables staff to teach nonscientists how to think both critically and scientifically, rather than telling them what to think (Niepold et al. 2007; Tran 2011; Quinn et al. 2012). Thus, instead of being merely the conveyor of facts, Aquarium educators help learners process information that is relative to their personal experiences and contexts.

Interactive, Web-Based Technologies

Interactive, web-based technologies will play an increasingly more important role in society by redefining how people learn, get information, engage with each other, and connect to the world around them (Linn et al. 2004; Ucko and Ellenbogen 2008). ISEIs must respond to these changes by using the strengths of the technology to stay relevant and hold the attention of today's youth (National Research Council 2009; The Ocean Project 2009b). To serve as a truly effective learning tool, the relevant app, interactive tool, or website must provide more than just verbal information presented in a digital interface. Technology must have a visually enticing display coupled with an interactive interface that both captivate and maintain the user's interest through the use of inquiry-based tools (Linn et al. 2004). Though by no means a replacement for direct, hands-on experience and observation, the availability of such technologies has been shown to complement, supplement, and even assist in an individual's ability to "connect" with the given subject matter (Ucko and Ellenbogen 2008). Additionally, by making these technologies available remotely as either an Internet or smartphone app, ISEIs are able to extend their ability to connect, engage, and educate the public beyond the walls of the Aquarium (The Ocean Project 2009b).

Inquiry, constructivism, and technology complement one another in a way that creates unique opportunities for learning that also builds skills in the long term. The National Science Education Standards state, "Science requires different [human] abilities" (National Research Council 2006). Human cognitive abilities include literacy, numeracy, logic, and graphicacy. Success in each of these areas is dependent, to varying degrees, on a student's ability to think and imagine spatially, a concept known as *spatial ability* (National Research Council 2006; Martinez et al. 2009). In particular, learning about spatial systems provides opportunities for deep meaning-making and skill building (Bednarz 1995; Drennon 2005).

Geographic Information Systems

GIS provides ISEIs with the ability to use interactive, cutting-edge spatial technologies to create an inherently constructivist learning environment that promotes scientific and spatial literacy in people of all ages by turning them into explorers. Geospatial visualizations help students use "critical thinking skills to examine real-world issues" and "provides geography, technology, and spatial analysis skills" in a science and/or humanities context (Demski 2011). Spatial thinking ability is a key component in students' ability to think critically, solve problems both inside and outside the classroom, and be an effective citizen in today's modern society (Libens et al. 2002; Bednarz et al. 2006; National Research Council 2006; Milson and Alibrandi 2008; Schultz et al. 2008; Martinez et al. 2009). Learners "need to be able to visualize the geospatial distribution of cultures, economies, and natural resources to fully understand the complexities of our global environment" (Guertin et al. 2012). Spatial content and geospatial technologies have been shown to improve scientific literacy, spatial reasoning, and higher-level thinking skills in people of all ages (Kidman and Palmer 2006; National Research Council 2006; Doering and Veletsianos 2007; Niepold et al. 2007; Schultz et al. 2008; Demski 2011; Hagevik 2011; Henry and Semple 2012; Kulo and Bodzin 2013). GIS is recognized as an interdisciplinary technology that supports high-level thinking and spatial reasoning, inquiry science, and open-ended investigations; directly correlates to real-world experience; allows students to visualize complex real-world problems; supports multiple modes of learning (Donaldson 2001; Bodzin and Anastasio 2006; National Research Council 2006); and is therefore a powerful tool for ISEIs.

Bednarz and colleagues (2006) contend that the ability to use images and geospatial technologies intelligently and critically is becoming a requirement to participate effectively as a citizen in modern society. Students and Aquarium guests can use GIS to solve real-life investigations and draw on skills that are crucial to developing higher-order thinking and problem solving (Ramirez and Althouse 1995; Sanders et al. 2002; Bodzin and Anastasio 2006). To provide contextual relevance and connect guests with a larger systemic understanding of their experience, the Aquarium has developed, implemented, and promoted different geospatial visualization programs.

Overview of the Aquarium's Geospatial Programs

Floor-to-Ceiling Exhibit Maps

The Aquarium of the Pacific uses various spatial platforms, ranging from simple static maps and images to user-driven, interactive geospatial visualizations and GIS, to connect guests to exhibits and ecosystems. Maps are used as geographical organizers throughout the Aquarium to connect the animals and exhibits to real places around the world. These stylized maps provide guests with context for the marine organisms and cultural aspects of the ocean region that they are experiencing. Similar maps are found at the entrance to the Aquarium's three main galleries: Tropical Pacific (the Western Pacific to Australia, figure 12.1a), North Pacific (Northern California to Alaska), and Southern California and Baja (temperate to subtropical regions of the Pacific Ocean, figure 12.1b). Adjacent to the June Keyes Penguin Habitat, a map of South America is marked with the typical distribution of Magellanic penguins (figure 12.1c). Many Aquarium guests are surprised to find that penguins live in environments other than Antarctica, especially the warmer climates of South America. The map also supports educators as they tell the story of four individual penguins in the collection, which were rescued when they became stranded off the coast of Brazil. Maps can also be found accompanying other major exhibits that are based on ecologically important but not widely known areas, such as the Gulf of California (figure 12.1d) and Coral Triangle (figure 12.1e). Both of these exhibits share a story with guests who are exploring the galleries, of previously unknown locations that have high endemism, high biodiversity, and face tremendous threat from human impact.



Figure 12.1. Floor-to-ceiling maps located throughout the Aquarium of the Pacific. Stylized maps surround the entrances of each of the Aquarium’s main galleries, including (a) the Tropical Pacific and (b) Southern California and Baja, to orient guests to the part of the world they are about to explore. A map is also used at (c) the entrance of the June Keys Penguin Habitat. Floor-to-ceiling maps are also showcased in the Aquarium’s galleries, including (d) Gulf of California, (e) Coral Triangle, and (f) US Exclusive Economic Zones. Photos courtesy of the Aquarium of the Pacific in Long Beach, California.

In addition to highlighting specific areas showcased in Aquarium exhibits, maps are used to generate discussion and broaden the public’s awareness of the world ocean. In 2013, Esri partnered with the Aquarium in the creation of a large-scale (10 × 23 ft) map of the US Exclusive Economic Zones (EEZs) using its high-resolution Ocean basemap (figure 12.1f). The EEZ map, located toward the end of the Tropical Gallery, allows guests to be visually struck by the vast expanse of US territories worldwide, including those that are underwater. The image has become a source of conversation between parents and children, who can be heard discussing places around the world to which they have a connection, through travel or other experiences. Using maps to set personal and place-based context has been a great success at the Aquarium.

Google Liquid Galaxy Exhibit

This blend of personal connection, maps, and technology has merged in the Liquid Galaxy installation (figure 12.2), provided to the Aquarium by Google. The exhibit was unveiled during the NOAA Office of Ocean Exploration and Research Forum, hosted by the Aquarium in July 2013. Google's Liquid Galaxy brings Google Earth to a large semicircle of screens, creating an immersive experience.



Figure 12.2. Google's Liquid Galaxy exhibit at the Aquarium of the Pacific. Photo courtesy of the Aquarium of the Pacific, Long Beach, California. Google Earth Map data ©2014 Google, Image ©2014 DigitalGlobe, Image ©2014 GeoForce Technologies; Data SIO, NOAA, US Navy, NGA, GEBCO.

The virtual globe interface of Google Earth allows people to view locations on Earth at any angle and from any distance (Schultz et al. 2008). The large surround screen displays of Liquid Galaxy provide guests the ability to explore, ask questions, and make discoveries as they “fly” around the world. Aquarium educators say guests have often expressed interest in continuing the experience once they leave, by installing the software on their home computers.

In February 2014, the Aquarium hosted a community event associated with a National Aeronautics and Space Administration (NASA)-funded teacher workshop. Interactive, educator-led stations around the Aquarium, including Liquid Galaxy, were designed to give teachers, parents, and students an opportunity to discover that data is everywhere. As expected, most guests instinctively used the interactive technology of Liquid Galaxy to find their own home, but more in-depth explorations were also observed. For example, a history teacher used it to introduce students to his home in Eastern Europe. He guided them on a three-dimensional journey through the history of

his town, showing the layout of the present-day city, where castle walls once stood, and how the streets radiated from a central location, indicating where the castle had been. By pairing his personal experience with the engaging and illustrative technology, this teacher was able to use the Aquarium to provide a memorable learning experience for his students. These quality engagements with Liquid Galaxy are similar to those observed by studies of Google Earth in K-12 classrooms (National Research Council 2006; Doering and Veletsianos 2007; Schultz et al. 2008; Guertin et al. 2012; Henry and Semple 2012), suggesting that this exhibit not only fosters spatial reasoning, but also has practical applications for informal learning environments.

NOAA's Science on a Sphere Exhibit

In 2011, the Aquarium of the Pacific became the first major aquarium with an SOS installation (figure 12.3). The Aquarium has additionally become the first institution with an SOS to create content that is focused directly on the most pressing issues facing today's oceans and share this material with other members of the SOS Users Network. Today, the Aquarium continues to be one of the most prolific producers of content for SOS, producing more than seven films, three of which were created entirely in-house. Content, which includes visualizations, datasets, films, and interpretive materials, is shared widely across the network of institutions using SOS, reaching 33 million people worldwide (NOAA 2014). To improve the effectiveness of the experiences offered, evaluations are also shared among the institutions in the SOS network (Goldman et al. 2010).

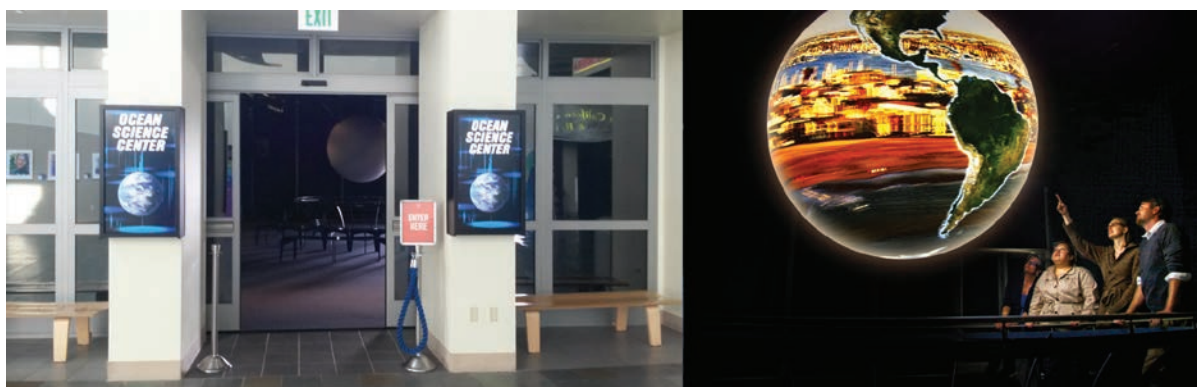


Figure 12.3. Science on a Sphere exhibit entrance and interactive sphere at the Aquarium of the Pacific.
Photos courtesy of the Aquarium of the Pacific, Long Beach, California.

The large-scale and high-definition quality images of SOS make it the centerpiece of the Aquarium's use of technology. Both attractive and adaptable, the sphere is a perfect platform for telling stories to Aquarium guests. Spherical films produced by the Aquarium of the Pacific are dynamic media pieces that combine datasets, imagery, and narratives about people to tell stories about a broad range of topics (Randol et al. 2012). These films, which range from four to eight minutes, focus on the following topics: sea level rise; the role of seaports; biodiversity; ocean exploration; coastal issues; marine debris; and how global data is collected through satellites, buoys, and remote-sensing technologies.

In addition to films, the Aquarium's Education Department uses the SOS platform to engage the public in deeper conversations about the ocean, climate, and earth systems. Through classroom programs and interpretations with public audiences (including school groups, families, and small

groups of adults), educators facilitate and navigate through a dialog, matched with datasets that help people connect to historical, and even recent, events, such as Hurricanes Katrina and Sandy, Typhoon Haiyan, and the Tohoku earthquake that led to the Fukushima nuclear power plant leak. Modeled data can show connectivity across the planet, such as the global connections of commercial airline traffic, Facebook Friend connections, and large-scale animal migrations. Animated datasets allow guests to see global processes over different temporal scales, such as water availability, warming from climate change, and changes in the spatial distribution of organisms. Conversations between educators and learners about these images build skills in interpreting spatial data and false-color images, understanding changes over space and time, and learning how these changes affect ocean life and humans (Goldman et al. 2010). Ultimately, all the Aquarium's SOS programs are designed to maximize the sphere platform by telling compelling narratives that help guests feel connected to marine and terrestrial environments while also increasing science literacy and awareness of conservation issues. A 2012 evaluation designed to explore the impact of the Aquarium's SOS films on its guests found that "visitors identify and remember the main messages presented in the programs" and the "presentations encourage discourse with others outside the aquarium" (Randol et al. 2012).

Aquarium of the Pacific's ArcGIS Online Website

Using the user-friendly ArcGIS Online interface with its hosting capabilities and templates, the Aquarium is busy creating interactive mapping apps and Story Map apps and making them available through an Esri-hosted site. The Aquarium's ArcGIS Online website (aop.maps.arcgis.com), shown in figure 12.4, has several interactive web maps and Story Map apps and provides links to other, non-ArcGIS Online geospatial online apps that are developed by and for the Aquarium.

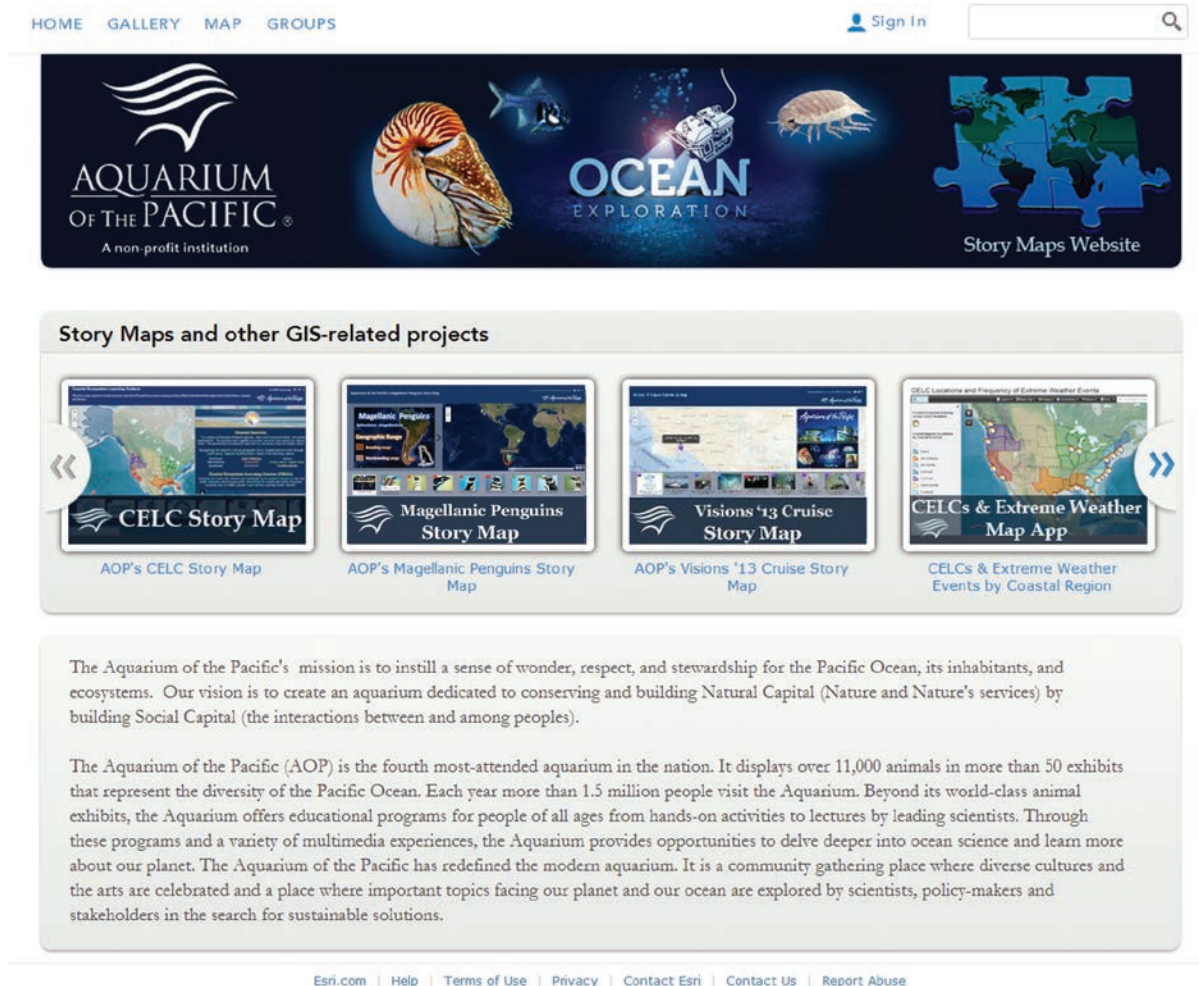


Figure 12.4. Screen capture of the Aquarium of the Pacific's ArcGIS Online home page, available online at aop.maps.arcgis.com. The interactive maps, Story Map apps, and apps referred to in figures 12.5 to 12.9 can be accessed using the Story Maps and Other GIS-Related Projects ribbon on the Aquarium's ArcGIS Online home page. Screen capture courtesy of Aquarium of the Pacific, Long Beach, California.

The Aquarium's ArcGIS Online home page showcases top geospatial apps, including the Coastal Ecosystem Learning Centers (CELC) Story Map (figure 12.5) created using the Esri Story Map Tour template and designed to introduce the Coastal America Partnership and its network of CELCs. The Coastal America Partnership is a partnership of federal, state, and local-agency governments and private organizations that work together to protect, preserve, and restore the US nation's coasts (The Coastal America Partnership 2014). The CELC Story Map begins with an explanation of the Coastal America Partnership, the mission of the partnership, and the location of CELCs within each coastal region (top panel). The user is able to travel between the different CELCs and see the name, address, website, image, and closeup map of each one (bottom panel).

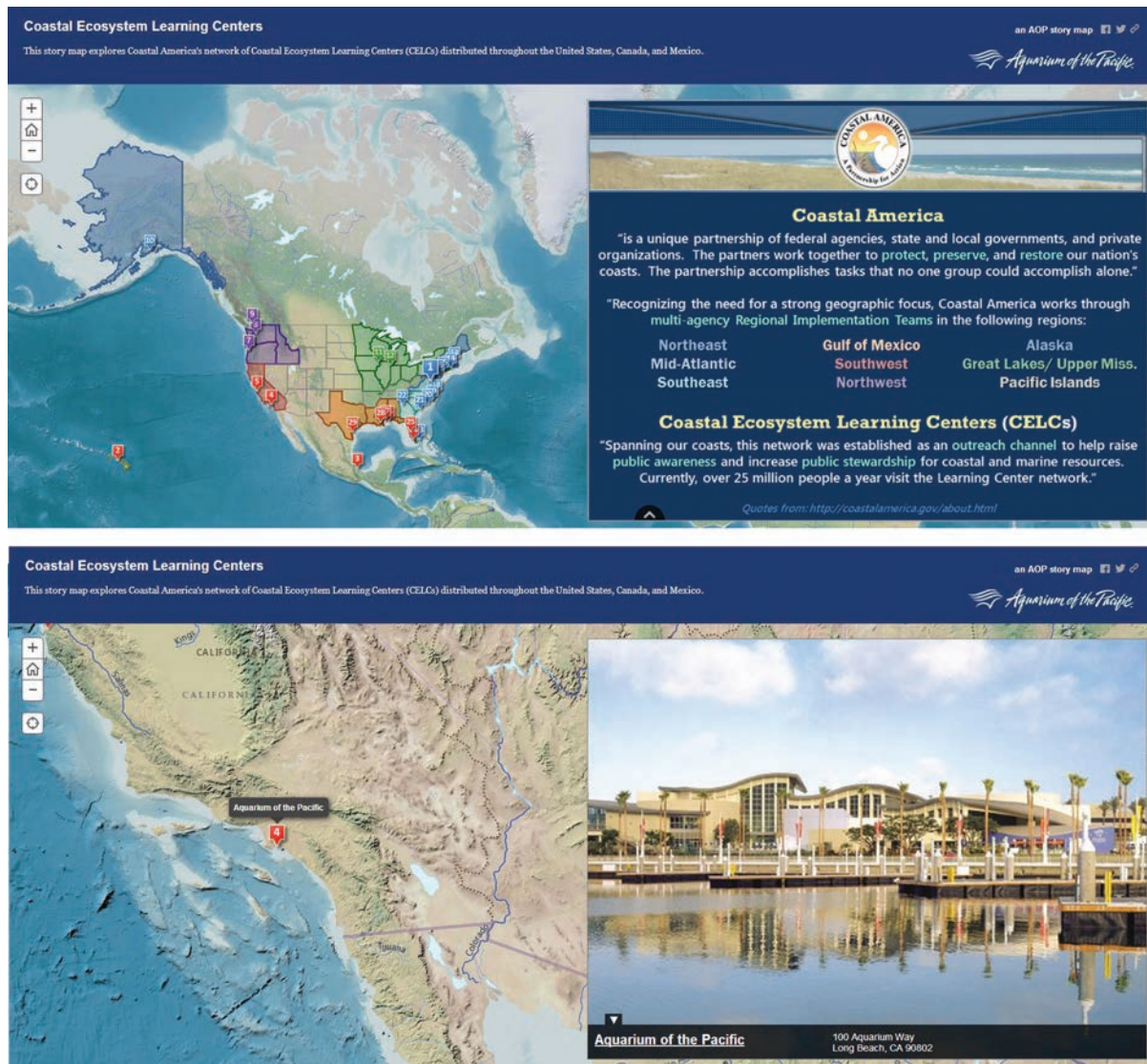


Figure 12.5. The Aquarium of the Pacific Coastal Ecosystem Learning Centers Story Map takes the user on an interactive, guided tour of aquariums and research centers throughout North America. The map begins by (top) showing a map of all the Coastal Ecosystem Learning Centers locations and explaining how they are all part of the Coastal America Partnership. The user can then (bottom) choose to go on an interactive tour to learn where specific learning centers are located and what they look like, with the images hyperlinked to the website for the given Coastal Ecosystem Learning Center. Screen captures courtesy of the Aquarium of the Pacific, Long Beach, California. Data sources: Coastal America Partnership and Coastal Ecosystem Learning Centers, GEBCO, NOAA NGDC, Natural Earth, and World Hydro Reference Overlay Map service.

Users who wish to learn more about CELCs may be interested in the CELC Extreme Weather by Coastal Region map app, which examines the frequency of extreme weather events for each of the nine coastal regions defined by Coastal America (figure 12.6). The goal of this Story Map app is to illustrate the partnership between these organizations and their efforts to increase public awareness and stewardship of marine and coastal ecosystems.

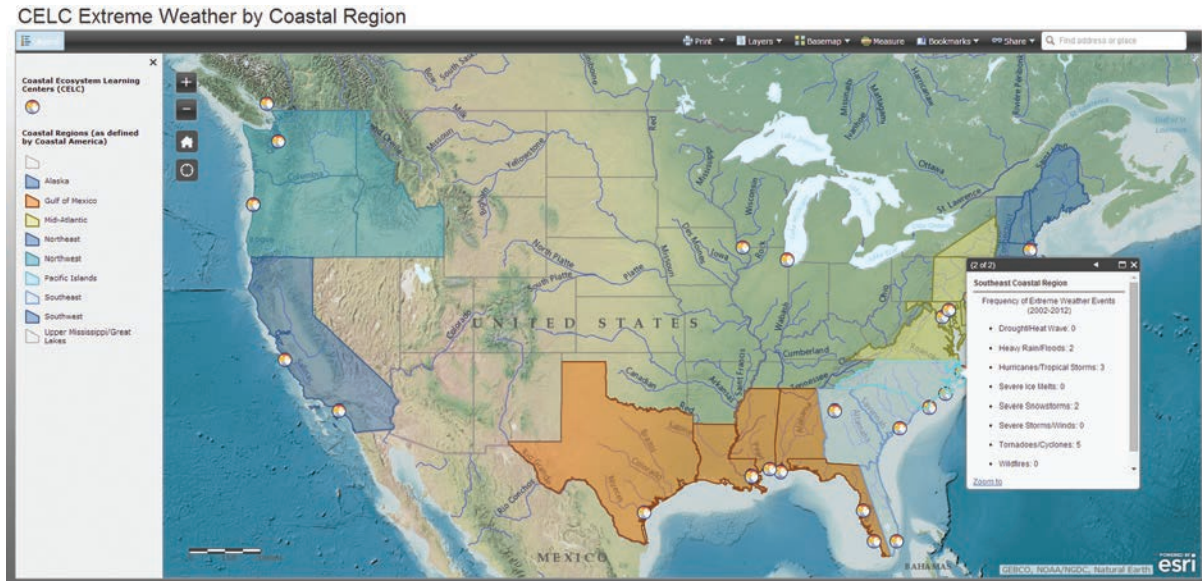


Figure 12.6. The CELC (Coastal Ecosystem Learning Centers) Extreme Weather by Coastal Region Story Map is an interactive ArcGIS Online map app that enables the user to visualize the distribution of Coastal Ecosystem Learning Centers throughout North America and examine the frequency of extreme weather events within each coastal region. Screen capture courtesy of the Aquarium of the Pacific, Long Beach, California. Data sources: Coastal America Partnership and Coastal Ecosystem Learning Centers, GEBCO, NOAA NGDC, Natural Earth, and World Hydro Reference Overlay Map service.

The Esri Story Map Tour template was also used to create a Story Map app about the Aquarium’s Magellanic penguins (figure 12.7), which provides information about each of the penguins including their nickname, personality traits, journey to the Aquarium, and a picture. Both the creation and release of this Story Map app were designed to coincide with the public debut of Heidi and Anderson, the first penguin chicks hatched at the Aquarium. Guests, who may already feel a connection with these charismatic animals, can use the Story Map app to learn more about the species, but also appreciate how all the penguins came to the Aquarium.

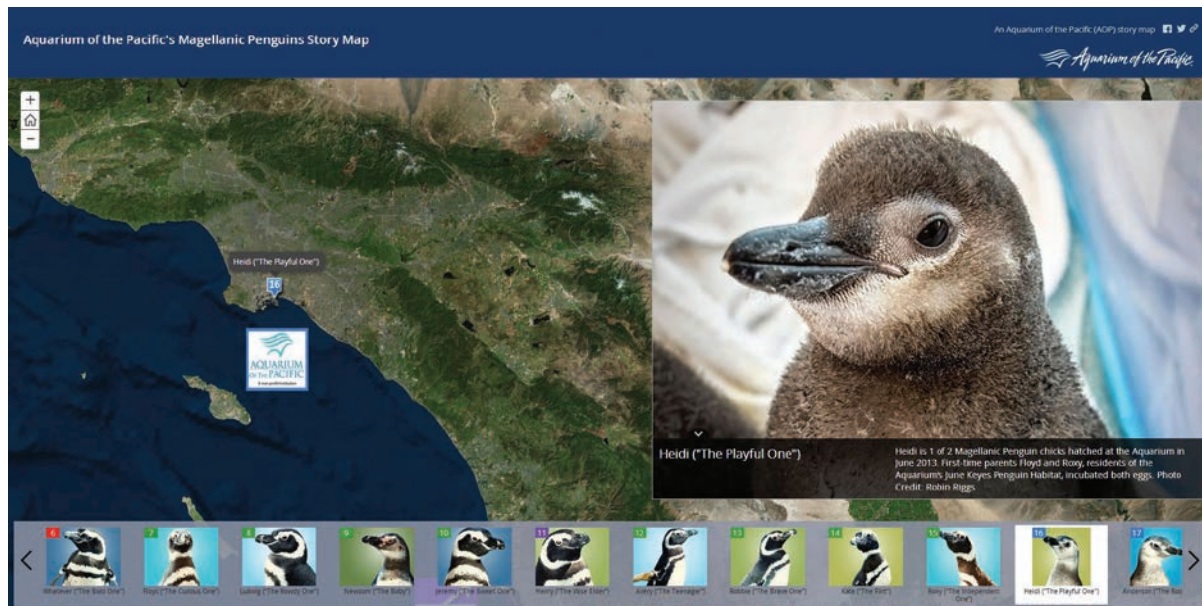


Figure 12.7. The Aquarium of the Pacific’s Magellanic Penguins Story Map. Screen capture and images courtesy of the Aquarium of the Pacific, Long Beach, California, and Robin Riggs. Sources: Esri, DigitalGlobe, Earthstar Geographics, CNES/Airbus DS, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Stand-Alone Geospatial Web Apps

In addition to the interactive maps and Story Map apps created using ArcGIS for Desktop software and ArcGIS Online service, the ribbon on the Aquarium’s ArcGIS Online home page also includes links to the following stand-alone spatial apps created by the Aquarium. The Aquarium’s Oceans in Motion app was designed to enable the Aquarium’s guests to view some of the images, videos, and spatial datasets featured in the Science on a Sphere film “Oceans in Motion.” The Sea Level Rise app provides an interactive, map-based interface in which the user can locate areas that are currently at risk of flooding and those that may be at risk in the future (figure 12.8), including the types and locations of infrastructure at risk from sea level rise.

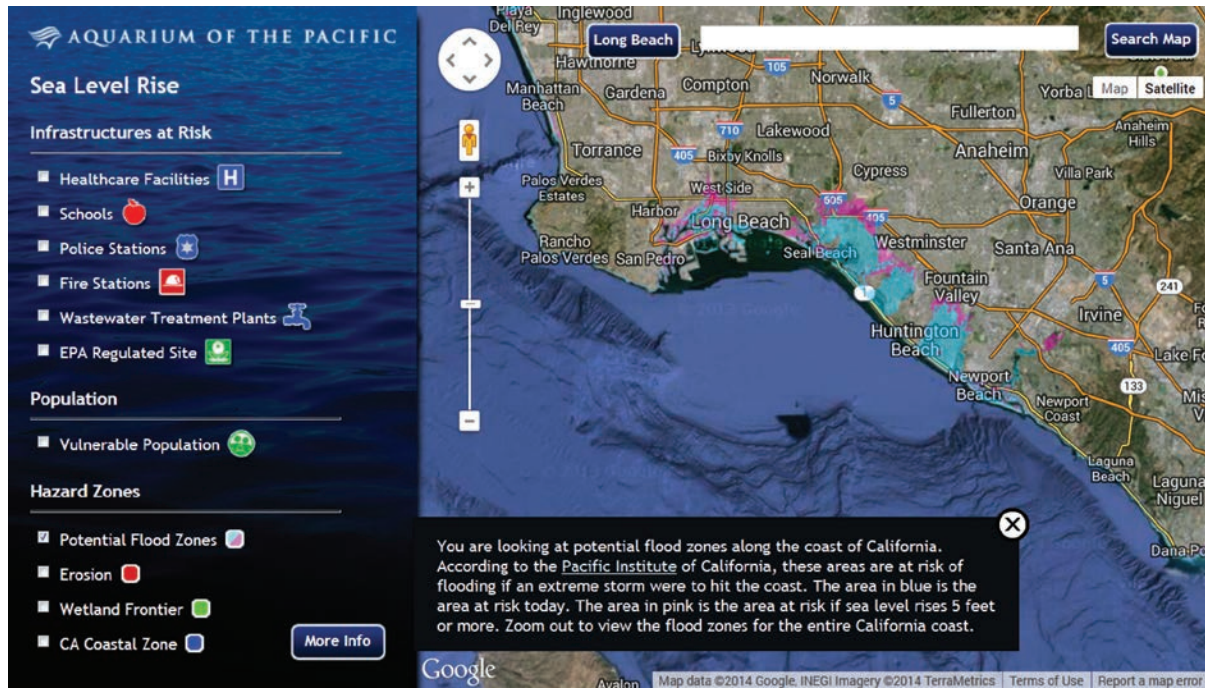


Figure 12.8. The Aquarium of the Pacific’s interactive Sea Level Rise app. The interactive interface of this app allows the user to identify the locations of vulnerable populations, infrastructures, and hazard zones as a result of flooding at current sea levels (shown in blue) and with a 5 ft rise in sea level (shown in pink). This app can be accessed through a link on the Aquarium’s ArcGIS Online home page, or directly at <http://www.aquariumofpacific.org/webapps/slr>. Screen capture and images courtesy of the Aquarium of the Pacific, Long Beach, California. Data sources: all data and research used in this app was based on a report prepared by the Pacific Institute, mapping support provided by Arc2Earth with a Google Earth basemap. Map data ©2014 Google, INEGI Imagery ©2014 TerraMetrics. Terms of Use | Report a map error.

The whale research app Southern California Whale Research Project: Connecting People, Science, and Whales (figure 12.9) is a product of the Aquarium’s partnership with the Cascadia Research Collective in Olympia, Washington. Since June 2010, the Aquarium has worked to collect data to help understand the movements of blue whales in Southern California. After photo identification of individual whales, the web-based app makes use of GIS and other software technologies to create a user-friendly geospatial database that provides access to whale sighting data for both scientists and the public. Although the focus of the project is on blue whales, the database also includes data collected on other cetacean species, including fin whales, gray whales, humpback whales, minke whales, orcas, Risso’s dolphins, bottlenose dolphins, and common dolphins. The interactive interface allows the user to query by species, individual whale, time period, and observed behaviors such as fluking and lunge feeding. The app also has the option to overlay layers that depict the study area and the shipping lanes of the large ships headed into the ports to see which whales are most often in danger. Although available to the public through the Aquarium’s website, this app is also used as an interpretative tool to engage guests in discussions about the risks that these endangered animals face and to make connections to conservation.



Figure 12.9. The Aquarium of the Pacific’s Southern California Whale Research Project: Connecting People, Science, and Whales app allows users not only to view the locations of cetacean species common to the Southern California area, but also filter the data by date, species, behavior (fluking, lunge feeding, and so forth), or even a specific whale. This app can be accessed through a link on the Aquarium’s ArcGIS Online home page or directly at <http://whaleproject.aquariumofpacific.org>. Screen capture and images courtesy of the Aquarium of the Pacific, Long Beach, California. Data sources: all data used in this app was based on ongoing research at the Aquarium of the Pacific, in collaboration with Cascadia Research Collective and Harbor Breeze Cruises. The app was created for the Aquarium of the Pacific by JLOOP, using a Google Earth basemap. Map data ©2014 Google Imagery, ©2014 TerraMetrics.

Apps such as these help extend learning experiences beyond the walls of the Aquarium by enabling guests to learn more about the world’s fisheries, marine protected areas, ocean currents, sea surface temperatures, dead zones, ocean acidification, and more. These apps also provide information on what we can do to preserve and restore marine ecosystems.

Geospatial Outreach through Teacher Workshops

The Aquarium hosts a number of annual workshops designed to offer classroom teachers professional development opportunities that provide new experiences, information, and resources. These Aquarium-facilitated workshops align with the needs of the teachers now transitioning to NGSS. The focus on experience, exposure, and access to scientists working in the field, rather than prewritten lesson plans, is in keeping with the goals of NGSS (National Research Council 2006 and 2009; Quinn et al. 2012). The Aquarium’s annual teacher professional development opportunities include the five-day Boeing Teacher Institute (BTI), two-day NASA Our Instrumented Earth workshop, and a one-day NOAA Office of Exploration and Research workshop. These opportunities provide extensive resources to teachers at no cost and support the development of curricula and activities that include ocean sciences and data interpretation in the classroom.

Although teachers may be aware of GIS and the beneficial role that it can play in the development of spatial reasoning skills in students, some are often overwhelmed by the idea of learning new software, intimidated by the idea of finding “real data,” and unsure of how best to incorporate GIS into their current curricula (Doering and Veletsianos 2007). To help address these problems,

workshops incorporate access to data along with simple GIS overviews. The Boeing Teacher Institute in 2013 provided a step-by-step tutorial (Lentz 2013b); and a 20-minute presentation, titled “Story Telling with Maps” (Lentz 2013d), introduced teachers to GIS and the power of the new Esri Story Map capabilities. A simple example that showed the locations of schools represented by the workshop participants was provided for teachers. NASA’s Our Instrumented Earth teacher workshop, in October 2013, had more data-focused content. During this two-day workshop, a 60-minute presentation, titled “An Introduction to GIS and Spatial Data,” walked the participants through finding spatial data, including the location sightings and geographic range of California sea lions (Lentz 2013a, 2013c), and bringing it into a GIS using the ArcGIS Online interface.

Preview of Future Geospatial Programs

The use of technology and geospatial programs has just begun and will continue to grow at the Aquarium of the Pacific. The planned expansion of Pacific Visions will provide state-of-the-art, innovative resources, creating an immersive experience for Aquarium guests. In much the same way that IMAX and OmniMAX theaters gave people the virtual ability to fly, Pacific Visions turns people into deep-sea explorers, storm chasers, and even allows them to join the pods of migrating whales. The Aquarium creates increasingly more advanced geospatial visualizations that are designed to both maximize the educational potential of existing resources, and prepare staff for the 2017 opening of Pacific Visions by providing training on how to most effectively interpret using interactive, GIS-based technologies.

Recognizing that narratives used in conjunction with visualization tools are an effective means of relaying scientific information to nonscientists (Ward 2006; Niepold et al. 2007), all upcoming geospatial materials are being designed to support specific stories.

New SOS Content

The Aquarium continues to develop its capacity to tell stories by building new interactive datasets that are designed to connect guests to important environmental issues, such as human population growth, ocean acidification, and marine animal migrations. Among the content currently under development are new SOS image sequences that show the Aquarium’s sea turtle rehabilitation and tracking program, launched in 2006.

This story, in particular, allows the Aquarium to leverage the popularity of sea turtles to provide information about behaviors and migration. The story can include threats to sea turtles: habitat loss, turtle egg harvesting, turtle consumption, jewelry made from turtle shells, unintentional bycatch from commercial fisheries, and, perhaps most common, severe injuries and death caused by turtles’ consumption of plastic bags and other man-made materials. By showing guests geospatial visualizations that are produced using the authentic tracking data from sea turtles rescued, rehabilitated, and released, the Aquarium is able to provide positive examples of its mission and commitment to conservation. Additionally, educators can provide guests with specific actions to take to reduce threats currently facing these animals.

New Story Map App

ArcGIS Online made it possible for organizations such as the Aquarium to quickly and easily produce attractive, interactive geospatial mapping apps and Story Map apps, using the new Esri Story Map app. In 2013, links to specific Aquarium-produced Story Map apps were released through social networks (Facebook and Twitter) to gauge public interest in web GIS. Because of positive feedback from these test releases, this content is being made available directly through the Aquarium's website. With 180,000 unique monthly visits from around the world, Aquarium Story Map apps have the potential for being a global educational tool.

Recognizing the power of this new medium, the Aquarium plans to create templates that are better suited to the specific requirements of the upcoming Story Map apps. Drawing on the concepts presented in the Aquarium's current CELC Story Map (see figure 12.5) and CELC Extreme Weather by Coastal Region mapping app (see figure 12.6), the Aquarium has a working draft of a CELC Story Map that is designed to help people connect to climate change by addressing local impacts. The Story Map app presents the user with different extreme weather events by providing personal accounts involving CELCs that experience or are at risk of experiencing these events. Users can select a specific extreme weather phenomenon (hurricanes, severe droughts, wildfires, blizzards, flooding, and so forth) to view a brief description, related images and diagrams, and an interactive map that allows the user to see past, present, and future at-risk areas. This map will also include the locations of CELCs, accompanied by photographic and written narratives of how that particular CELC was affected by the weather. For example, Audubon's Aquarium of the Americas, located in New Orleans, Louisiana, was impacted when Hurricane Katrina hit in 2005. Structurally, the facility was still intact, but subsequent flooding and electrical issues created unstable life support systems; most of the animal collection was lost. Incredibly, the facility was able to rebuild and open a year later (*Los Angeles Times* 2006). During Hurricane Sandy in 2012, another CELC, the New York Aquarium, flooded and sustained severe damage. Eighteen staff members cared for the collection of animals, and the facility reopened seven months later (Fears 2012). Combining interactive geospatial visualizations of extreme weather events with personal narratives, this Story Map app connects local places or places that people have visited to the very real events and impacts of severe weather.

The Aquarium continues to create new Story Map apps to connect its guests with geospatial technologies. The possibilities are endless, and the stories are varied. Upcoming projects include a virtual tour of the Aquarium that pairs exhibit images with the actual geographic location for which the exhibit was modeled, a depiction of local watersheds and the story of where Southern California gets its water, and narratives of ambassador Aquarium animals that represent threatened or endangered counterparts. Still other visualizations can tell the great success stories of recovered populations, sustainable fisheries, and responsible management. Ultimately, the Aquarium plans to use Story Map apps to connect people to real places and issues by making topics such as climate change, habitat loss, and threatened and endangered populations easier to understand and relate to.

Conclusion

Our world is rapidly changing. The way people learn, communicate, and get information about our planet is evolving, and this evolution is happening more quickly than ever before. To stay involved, the public needs trusted sources of scientific data, information, and tools to critically evaluate this content. The Aquarium of the Pacific and fellow Informal Science Education Institutions are the facilitators of this current science and must stay connected to new technologies and storytelling

strategies to engage, connect, and inspire guests to take action. Through captivating animal exhibits and innovative technologies, the Aquarium of the Pacific is connecting people to the physical and biological world around them, increasing the capacity of its audience to think critically about conservation, and redefining what it means to be an aquarium.

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Supplemental Resources

Dawn J. Wright, ed.; 2016; *Ocean Solutions, Earth Solutions*, second edition; http://dx.doi.org/10.17128/9781589484603_12d

For the digital content that goes with this chapter, explained in the following sections, go to the following links or QR codes. Hyperlinks are also available in the book’s online resources (esri.com/esripress-resources/ocean-solutions-2e) to view the Story Map apps and visit the Aquarium website.

Coastal America Partnership and CELCs

- Story Map app of the Coastal America Partnership and its network of Coastal Ecosystem Learning Centers (CELCs), at <http://bit.ly/1pQGvsR>



The Coastal America Partnership is a partnership of federal, state, and local-agency governments and private organizations that work together to protect, preserve, and restore the US nation's coasts. The Story Map app begins with an explanation of the Coastal America Partnership, the mission of the partnership, and location of CELCs within each coastal region. The user is able to travel between the different CELCs and see the name, address, website, image, and closeup map of each one.

Magellanic Penguins

- Magellanic Penguins Story Map, at <http://bit.ly/1pQGO73>



This Magellanic Penguins Story Map provides information about each of the penguins living at the Aquarium of the Pacific, including their nickname, personality traits, journey to the Aquarium, and a picture. Both the creation and release of this Story Map app were designed to coincide with the public debut of Heidi and Anderson, the first penguin chicks hatched at the Aquarium. Guests, who may already feel a connection with these charismatic animals, can use the Story Map app to not only learn more about the species, but also appreciate how each penguin came to the Aquarium.

Aquarium of the Pacific

- Aquarium of the Pacific website, at <http://aop.maps.arcgis.com/home>



The Aquarium has quickly begun creating interactive mapping apps and Story Map apps and making them available through this Esri-hosted site, which currently has a number of interactive web maps and Story Map apps and provides links to other geospatial, online apps developed by and for the Aquarium.

CHAPTER 13

Uncovering the Oceans through Marinescape Geovisualization

Rosaline Canessa, Robert Newell, and Cathryn R. Brandon

Abstract

More often than not, geographic representation of the marine environment strips the ecosystem of its richness in habitats, biodiversity, and verticality. Mapping the marine environment in GIS results in marine features that are represented as a two-dimensional plane on the sea surface or as bare bathymetry. These visualizations are geographically accurate but not visually pleasing nor comprehensive in representing marine ecosystems. In contrast, gaming and virtual reality programs produce attractive visuals but typically are not geographically referenced. This chapter explores marinescape geovisualization, the integration of visual simulation with map-based geography for marine environments. First, a review of the progress made, from conventional two-dimensional maps to immersive and interactive four-dimensional models for marine environments, is presented. Subsequently, a case study of a marinescape geovisualization model, which integrates GIS and landscape visualization software of an offshore marine protected area, is described along with feedback provided by marine protected area planners and scientists. Finally, the chapter concludes with insights on key research and development issues to advance marinescape geovisualization.

Introduction

Marine environments are under stress from human-use activities (Hinrichsen 2011). These impacts are exacerbated as marine environments are poorly understood in comparison with terrestrial environments. Other than scientists and those who scuba dive, the public and even decision-makers have relatively little knowledge of the marine environment. Maps have long been the predominant visual currency for land-use planning, but some maps are too abstract or schematic, making it difficult for the layperson to relate mapped information to their real-world experience or cognition (Paar 2006); and, in fact, they can contribute to confusion and errors in orientation (Lewis and Sheppard 2006). This suggestion is particularly relevant to the marine environment, for which there

are no equivalents of satellite images or orthophotos to drape over bathymetry. You have only to look at the difference between Google Earth and Google Oceans to appreciate the limitations in mapping marine environments. Maps and virtual globes often depict the open ocean as a blank, blue space or with bare bathymetry that belies the dimensionality, fluidity, diversity, complexity, and significance that lie under the sea surface and could compromise informed decision-making and public understanding. There is a clear need for improved tools to communicate complicated and diverse ocean and coastal information to support marine planning and public outreach (Jude et al. 2007).

As an alternative to conventional maps and GIS, landscape visualization has been promoted as a new common communication currency that is integral to land-use planning (Lange 2001; Orland et al. 2001). Combining graphic technology and art to create varying degrees of realism, landscape visualization aims to better situate the user within a simulated landscape. Geovisualization is the integration of visual simulation with map-based geography. Geovisualization reflects a rising spatial literacy in the public, which is increasingly exposed to simulated games and virtual reality. Thus, the public has high expectations for a more realistic, accurate, intuitive, engaging, and accessible representation of the world, which is rich in structure, texture, and movement (Paar 2006). Landscape visualizations have yielded positive results in development planning, forestry management, climate change visioning, changing public perceptions, and adaptive response (e.g., Lewis and Sheppard 2006; Burch et al. 2009). However, marinescape geovisualization lags far behind (Canessa 2008). Efforts such as Google's foray into a "street view under the sea" are an indicator that the marine environment is a new frontier of geovisualization.

One of the key challenges of depicting and visualizing marine environments is the inherent three-dimensional (3D), volumetric, and time-dependent aspects of marine environments, such as biological, chemical, and physical processes (Wright and Goodchild 1997; Gold et al. 2005; Wright et al. 2007; Goralski and Gold 2008). A 3D GIS or geovirtual environment allows not only the sea surface to be portrayed, but also pelagic and benthic environments altogether. Marine data structures have been designed to store depth and time values, but the visualization capabilities of displaying these dimensions have room for improvement (Wright et al. 2007), particularly in integrating spatial data with such technology as game engines and augmented reality.

This chapter explores the evolution of marinescape geovisualization to current innovation, presents a case study that applies landscape visualization to a marine area, and charts a research and development agenda for marinescape geovisualization. The following sections provide an overview of the variety of coastal and marine geovisualizations. Each section refers to a geovisualization that assumes a specific dimensionality and discusses the spatial aspects and potential applications associated with the dimensional representation.

Development of Marinescape Geovisualization

Exploring the Surface: Conventional Maps and 2D Dimensionality

Many conventional maps depict the ocean as the negative or contrasting space (graphically speaking) to land contours; and accordingly, they typically communicate marine information in reference to terrestrial geography (e.g., coastal sites of marine habitat, locations of coastal communities, oceanic transport routes, and so forth). Conventional maps are two-dimensional (2D) and assume an overhead perspective. Thus, they are limited in the amount of detailed information that can be visually conveyed regarding the water column and seafloor. However, because of their simplicity, maps are relatively easy to create and communicate information clearly; therefore, they have been

(and continue to be) employed extensively to communicate a range of information regarding coastal and marine spaces (Kraak 2011; MacEachren and Kraak 2001).

Because of their 2D format, such maps can be particularly effective in clearly conveying surface characteristics of the ocean. For example, the work of the Geophysical Fluid Dynamics Laboratory (2008) in mapping dynamic ocean surface temperatures produced visualizations that provide a comprehensive and extensive view of dynamic heat flow across the oceans of the world. Maps are also useful for displaying vector data oriented along the ocean surface, and thus can clearly communicate essential nautical information, such as the directions of ocean currents along the surface (e.g., as seen through the interactive map system of Oceanweather [2014]). Furthermore, although 2D maps do not contain a depth axis, they are useful for identifying locational and area-based data, and thus can identify subsurface elements as they align with the ocean's surface, examples of this being research conducted through the US National Centers for Coastal Ocean Science on coral reef habitat ranges and reef fish distributions (e.g., Costa et al. 2014).

Maps have the ability to capture and convey biophysical data on extensive ranges of marine space (e.g., global temperatures, currents, and large areas of habitat). This capability positions maps as effective tools for synthesizing, analyzing, and communicating information on certain large-scale environmental issues. For example, the National Center for Ecological Analysis and Synthesis synthesized data on a comprehensive suite of environmental threats to marine environments (e.g., pollution, invasive species, and bycatch fishing) and mapped their cumulative impacts around the globe (Halpern et al. 2008) (figure 13.1). Although the map does not provide detailed information on subsurface impacts and which threats have the most impact at certain localities, the visualization provides a broad, global-scale impression of marine environments at risk. In addition, because maps have the ability to clearly communicate surface information (as discussed), they are particularly effective in capturing and conveying potential environmental impacts that can result from surface pollutants and potential associated sources of oil such as marine vessels (Serra-Sogas et al. 2008). Examples include an interactive map that depicts the British Petroleum (BP) oil spill of April 2010 posted online (accessible from <http://nyti.ms/1o7IjNJ>) through the *New York Times* (Aigner et al. 2010). Because of its simple 2D format and clear graphical contrast between oil and water, the visualization clearly illustrates the extent of oil spills, and thus marine spaces at risk.

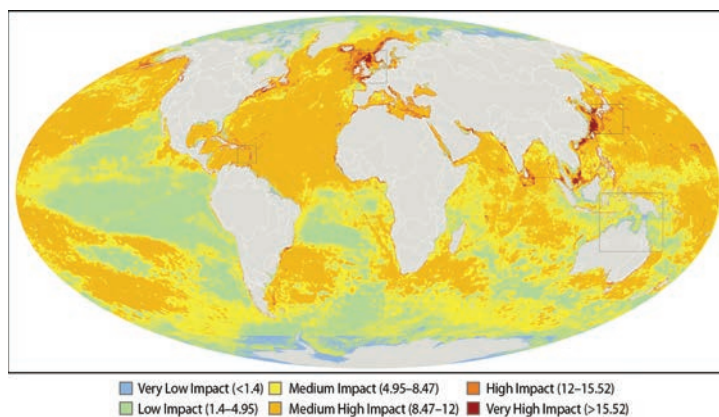


Figure 13.1. A global map of human impacts to marine ecosystems. Image courtesy of US National Center for Ecological Analysis and Synthesis.

Another common ocean-based environmental issue depicted through map visualizations is sea level rise induced through climate change. However, because 2D maps do not include a depth axis, they cannot geometrically display a rise in water; therefore, sea level rise is depicted through the

adjacent topological relationship between the terrestrial and marine contours. The effect of sea level rise in a 2D plane is the ocean essentially “eating” away the land, making these maps still meaningful (if not entirely geometrically accurate) tools for communicating climate change impacts. Examples include the interactive maps of varying sea level rises developed through the University of Arizona’s Department of Geosciences, made publicly available through the ArcGIS Viewer for Silverlight web application (methodology described in Weiss et al. 2011).

Advancements in, and increasing availability of, GIS technology over the last couple of decades provide new opportunities for creating innovative geovisualization projects that integrate biophysical data with social, economic, and cultural information for marine and coastal environments (Rodríguez et al. 2009; Green 2010; Souto et al. 2012). An example includes the work of Longdill and colleagues (2008), who used ArcGIS software to map a variety of information associated with the Bay of Plenty, New Zealand, including biophysical characteristics, economic activities, and local cultural values, and used this integrated mapping to help identify suitable and sustainable sites for aquaculture development. Another example includes the work of Ruiz-Frau and colleagues (2011), who, also using ArcGIS, developed spatial representations of ecological, economic, and cultural values associated with the coast of Wales and held by diverse stakeholders for the purpose of informing site-specific marine management practices.

Exploring the Seafloor: Moving to 2.5D and 3D Dimensionality

2.5D Dimensionality

Advancements in multibeam bathymetry techniques and software throughout the late 1970s and early 1980s made it possible to capture and characterize large areas of the seafloor, allowing humans to virtually explore the terrain below the ocean’s surface (Tyee 1986). Many map-type visualizations have incorporated bathymetric information and expressed it through the two-and-a-half dimensional (2.5D) perspective, a method of conveying seafloor terrain through contours or relief surfaces. Geovisualizations in 2.5D are limited in that they do not effectively capture bathymetric perspectives. However, they can be useful for providing seafloor information to people that readily use and understand map formats, such as those in the nautical professions (Scheepens et al. 2014). As can be seen with the Story Map app featured in figure 13.2, the 2.5D perspective holds the advantage of being able to convey planar information related to ocean surface (in this case, the route of HMS *Titanic*), while still capturing and displaying some subsurface features.

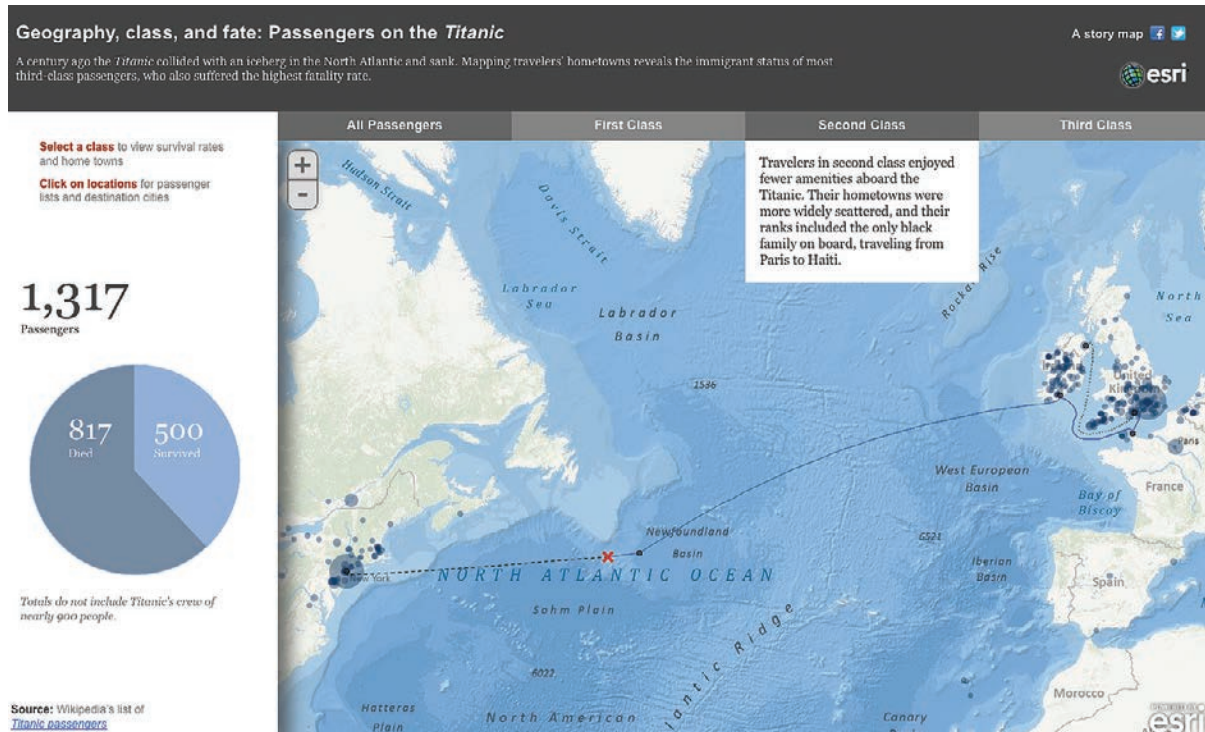


Figure 13.2 Esri Story Map app displays the travel route of the *Titanic*. By Esri; data sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, Geonames.org, and other contributors.

Public dissemination of and exposure to information on the shape and character of the seafloor has increased through the development of open-source ocean visualization applications that assume a 2.5D perspective. Virtual Oceans, developed through the Lamont-Doherty Earth Observatory at Columbia University, is an example of a GeoMap app-based application that conveys multibeam bathymetry data in 2.5D format, using an interactive globe browser supported by the National Aeronautics and Space Administration (NASA) World Wind (Marine Geoscience Data System 2011). Of more significance in terms of public outreach is the 2.5D representation of the ocean floor incorporated in Google Earth. Google Earth allows anyone with an Internet connection access to detailed information of the planet's geography (Shufeldt et al. 2012). Google Earth's inclusion of seafloor details holds important implications for public understanding of the ocean because it represents a shift from strictly 2D, surface-focused perspectives of marine spaces (that historically have dominated conventional maps) to perspectives that provide glimpses of what lies below the ocean's surface.

3D Dimensionality

Relief-type visualizations can convey coarse information regarding the seafloor; however, they are limited in that they do not employ a depth axis, and thus cannot portray the full perspectives of bathymetry. To explicitly capture the geomorphological features of the seafloor, a geovisualization must be completely 3D. Many 3D marine geovisualizations assume a “sandbox” perspective (figure 13.3), which allows users to examine and compare different terrain features of the seafloor (e.g., displays of the seafloor shelves in the same frame as the slopes). Such a perspective is particularly useful for gaining insights on subsurface geomorphology, local ecology, and sensitive habitats (Lundblad et al. 2006).

Several different applications have been used to construct 3D bathymetric models, including Geological Surveying and Investigation in 3 Dimensions (GSI3D) (Kessler et al. 2009), 3D GeoModeller (Calcagno et al. 2008), and Advanced Visual Systems (AVS) (2014). However, Fledermaus (a product of Quality Positioning Services, or QPS) is arguably among the most popular software used specifically for creating 3D bathymetric visualizations; and its applications in marine resource management have been the subject of much research. Fledermaus applications include the work of Cooper and colleagues (2011) on modeling the outcomes of potential strategies for gravel habitat restoration and the work of Weaver and colleagues (2006) on modeling and characterizing the marine habitat in the Tortugas South Reserve (Florida Keys National Marine Sanctuary). An important feature of Fledermaus is that it can be used to create digital elevation models that are compatible with ArcGIS, allowing for in-depth spatial analysis using bathymetric models. An example of this workflow includes the study of Rengstorf and colleagues (2012) on the use of different bathymetric models for marine habitat suitability analysis, which used Fledermaus to create the bathymetric models and ArcGIS to analyze terrain attributes.

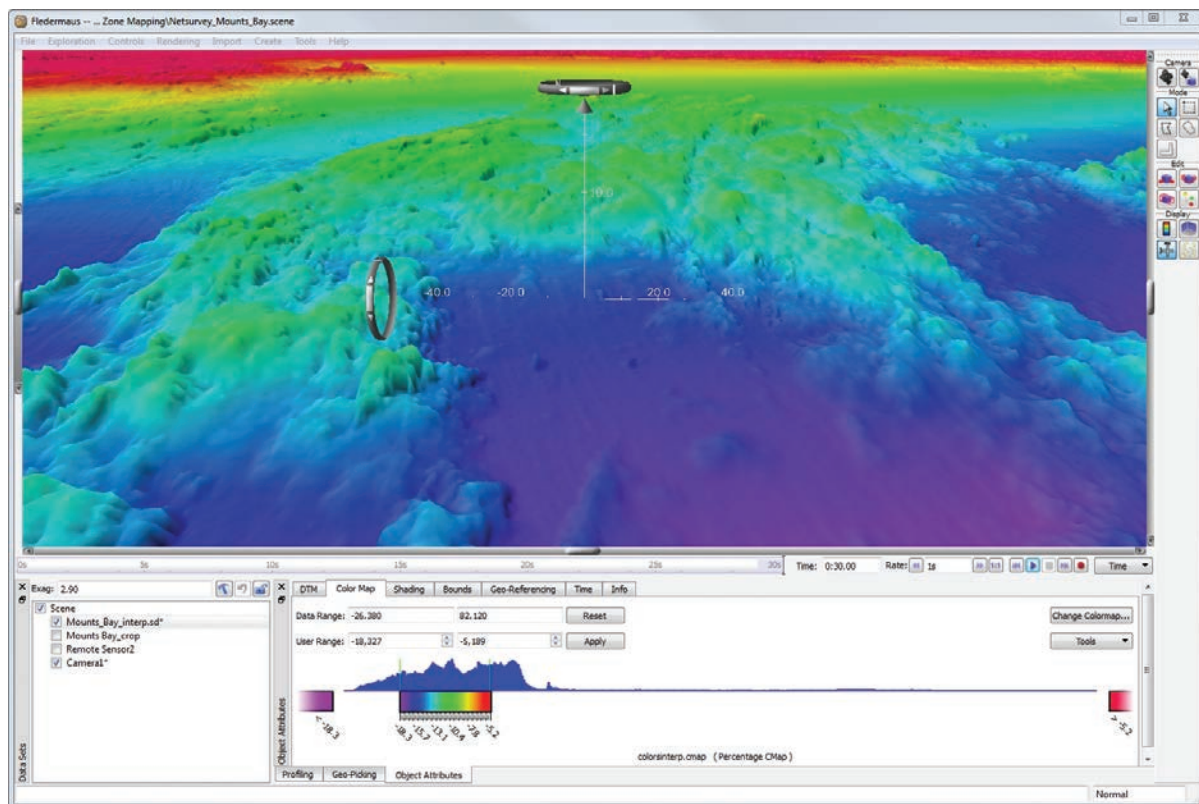


Figure 13.3 Screen capture of Fledermaus bathymetric modeling software. Courtesy of Quality Positioning Services BV (QPS).

The modeling software noted here is highly specialized and requires particular skill sets to use effectively. However, effective coastal management requires multidisciplinary approaches and input from a range of different actors and stakeholders (Cicin-Sain and Belfiore 2005). Recognizing this need, Collaborative Ocean Visualization Environment (COVE) was developed as a user-friendly, 3D marine geovisualization system that can facilitate collaborative work within the scientific community (COVE 2009). COVE was specifically designed through the feedback of different scientists and engineers to ensure its user-friendliness and utility in multidisciplinary projects (Grochow et al.

2008). Systems such as COVE allow for the use of sophisticated visualizations in management projects while simultaneously maintaining inclusivity and collaboration.

Exploring Place: Immersive Geovisualizations

Geovisualizations that aim to capture and convey bathymetry using the 3D, sandbox perspective often focus on the seafloor, excluding elements found in the water column and above the surface. However, a comprehensive and accurate portrayal of the marine environment must incorporate all dimensions of marine space, and thus include elements and interactions of the water column and transsurface. The challenge in constructing such a visualization is that marine environments consist of elements that span multidimensional space; thus, adding certain elements to a marine/coastal geovisualization can potentially obscure others. Immersive geovisualizations provide a possible solution to this issue by allowing users to navigate through and around elements, permitting visual access to all aspects of the visualization and thus visually accommodating for multidimensionality. Accordingly, immersive geovisualizations can be constructed with a high degree of realism, detail, and accuracy (in terms of capturing more real-life elements).

The application of immersive geovisualizations in natural resource planning and land-use management has been explored in the terrestrial context (Lewis and Sheppard 2006; Schroth et al. 2006; Schroth et al. 2009; Sheppard et al. 2011). However, research and applications of immersive coastal and marine geovisualizations are still in their infancy. Among the little work done are projects such as Ecosystem Science and Visualization Group (EcoViz), the Nereus Program, and the North West Shelf Joint Environmental Management Study (NWSJEMS) (2010). EcoViz is a research project within the California State University System that builds visualizations of marine protected areas (MPAs) (figure 13.4) for the purposes of public education, informing decision-makers, and supporting the marine management practices of MPAs (EcoViz 2011). The Nereus Program is a collaboration between the University of British Columbia and the Nippon Foundation that focuses on fisheries impacts research. Nereus uses immersive visualizations for the purpose of communicating complex scientific information to the broader public (Nereus Program 2013). NWSJEMS is a research project based in Western Australia, aimed at developing and conducting methods that support sustainable management practices of marine environments. Similar to Nereus, NWSJEMS uses immersive geovisualizations (namely, an animation referred to as “shelf life”) to communicate outcomes of their work and educate the public on multisector management in marine ecosystems (NWSJEMS 2010).

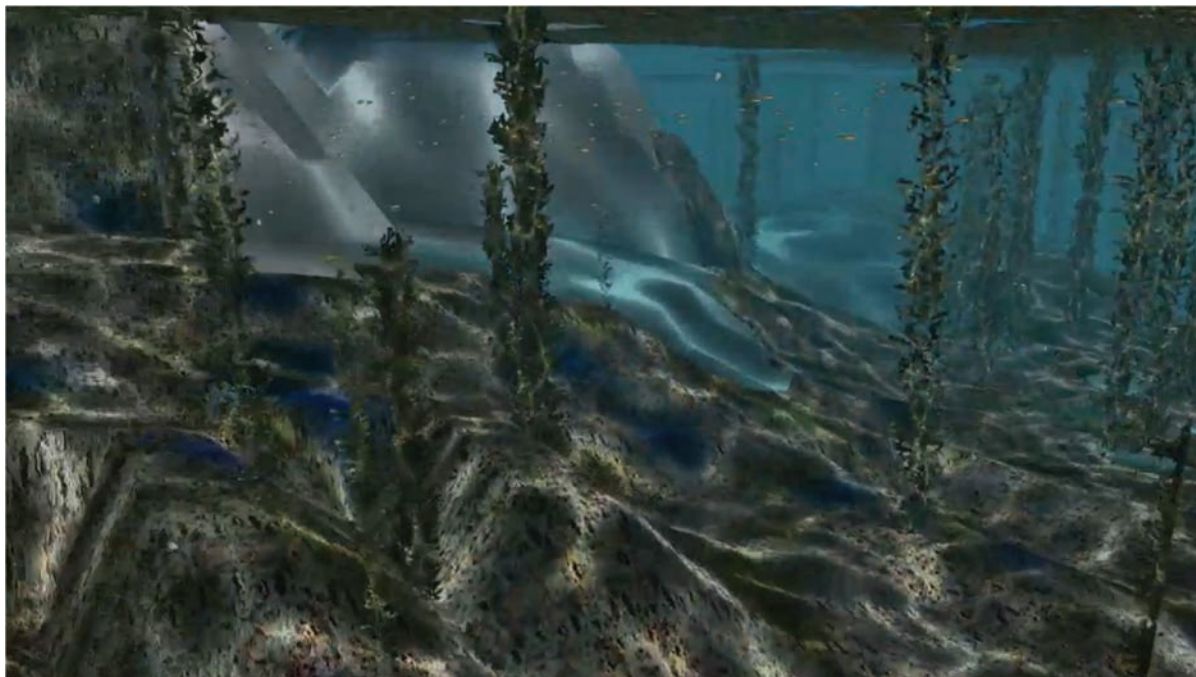


Figure 13.4 Immersive visualization of Point Lobos Marine Protected Area. By Fred Watson, Alberto Guzman, Tom Thein; footage by Kip Evans; courtesy of University Corporation at Monterey Bay.

An important similarity among the applications of immersive geovisualizations described here is that they all were used to communicate scientific information to broader groups (i.e., the public). Immersive geovisualizations are powerful tools for communicating place-based information, meaning that they have the ability to situate someone in a “place” and provide them with a better sense of represented location (Turner et al. 2013). Such a feature is important for increasing understanding of the environment and making sound management decisions (Lewis and Sheppard 2006; Phadke 2010). This feature of immersive visualizations will become increasingly more significant for public understanding of the marine environment as Google’s Ocean Street View project progresses. Launched in 2012, this project involves the development of publicly available interactive visualizations (accessible from <https://www.google.com/maps/views/streetview/oceans?gl=us>) that immerse the user in the marine environment. As Google continues to build this virtual underwater world, the public’s access to marine “places” increases, which potentially can contribute to public familiarity and understanding of marine environments and thus make the world below the ocean’s surface seem less “alien.”

Exploring the Living Sea: Incorporating Time and Interactivity

Marine and coastal environments are dynamic places with complex interactions; therefore, accurately capturing the “reality” of these environments in geovisualizations requires incorporation of fourth-dimensional properties (Beegle-Krause et al. 2010). Such a task can be data intensive and challenging; thus, visualizations that involve temporal dimensions often focus on patterns or trends of specific aspects of the marine environment while excluding or simplifying other temporal dynamics. For example, the Nereus Project constructed a visualization that is specifically designed to convey the impacts of overfishing from 1950 to the present, by displaying a marine scene with fish populations that fluctuate in density as a counter that represents the year advances (Nereus Program 2010). In

another example, the BP oil spill visualization posted in the *New York Times* is interactive, allowing users to select different dates to examine the oil spill pattern and expansion throughout the Gulf of Mexico over time (Aigner et al. 2010).

Over the last couple of decades, the computer game industry has propelled technological advancements in the development of dynamic virtual spaces. Accordingly, game engines have been suggested as potentially powerful tools for constructing geovisualizations using 3D and four-dimensional (4D) properties (Gold et al. 2004). *Infinite Scuba* (a diving simulation game) serves as an illustrative example of how a game platform can be used to develop a dynamic and sophisticated marine geovisualization. *Infinite Scuba* was developed through partnership between the Professional Association of Diving Instructors (PADI) and Cascade Game Foundry for the purpose of emulating a realistic and enjoyable virtual diving experience. The virtual environment in *Infinite Scuba* is dynamic and contains a multitude of interacting elements such as marine life (figure 13.5), demonstrating the potential that computer game technology has for developing realistic, immersive geovisualizations.

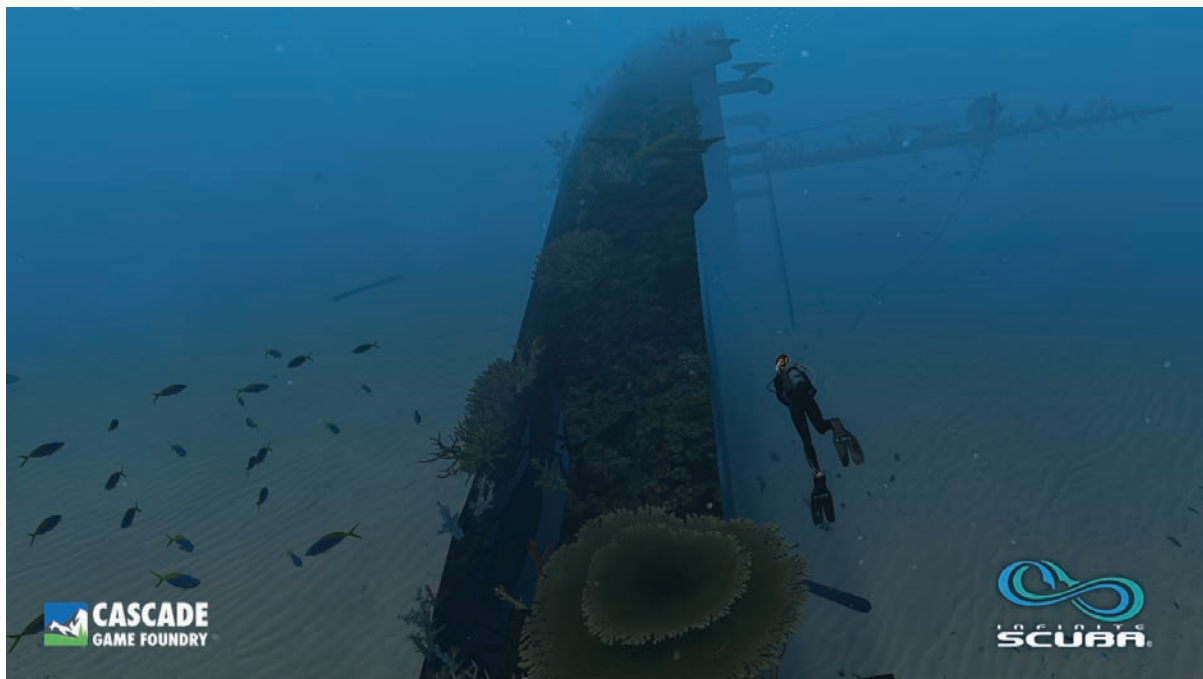


Figure 13.5. Screen capture from the *Infinite Scuba* video game. Courtesy of Cascade Game Foundry Corp.
Copyright © Cascade Game Foundry Corp., 2014.

Marinescape Geovisualization Case Study: SGaan Kinghlas–Bowie Seamount Background

SGaan Kinghlas–Bowie Seamount rises from 3,000 m depth to within 25 m of the sea surface, 180 km west of Haida Gwaii on Canada’s Pacific coast (figure 13.6). Seamounts are productive habitats as deep, cold waters upwell when encountering the seamount structure, bringing in nutrients. Seamounts can also serve as stepping stones for migratory species. SGaan Kinghlas–Bowie Seamount

is home to a diversity of species from deep water to coastal species, brought to the seamount through coastal gyres (Canessa et al. 2003). In recognition of these characteristics, SGaan Kinghlas–Bowie Seamount was declared a federal MPA in 2008. However, given its remoteness and the expense in getting there, SGaan Kinghlas–Bowie Seamount has remained largely unexplored and inaccessible, except to a handful of scientists and fishermen. SGaan Kinghlas–Bowie Seamount is not only physically remote but cognitively remote, with a lack of information for making management and planning decisions and for the public to engage. For both these reasons, the objectives of the SGaan Kinghlas–Bowie Seamount MPA include scientific study and public engagement.



Figure 13.6. SGaan Kinghlas–Bowie Seamount (after Canessa et al. [2003]). By the authors, based on Canessa et al. (2003). Data from National Geophysical Data Center, National Environmental Satellite Data and Information Service.

Initially, information on SGaan Kinghlas–Bowie Seamount was gleaned from videos and photographs taken by scientists. These offerings comprised snapshots of small portions of the vast seamount complex. This sampling changed significantly with the acquisition of multibeam data, which enabled the development of a 2.5D model in ArcGIS of the top 200 m of the seamount (figure 13.7). For the first time, it was possible to see the “landscape” of the seamount, at least the top 200 m. The images clearly show features such as the ridge, plateaus, and hills. Furthermore, it was possible to navigate through different perspectives of the seamount as in a “dive-through.” Although the 2.5D perspective shows more detail in the physical form of the summit, it is devoid of geophysical texture and biological richness. Thus, it can relay the impression that SGaan Kinghlas–Bowie Seamount is barren and mislead viewers on its ecological value. Whether users are politicians, planners, policy makers, or the public, this impression can lead to uninformed priorities and decisions.

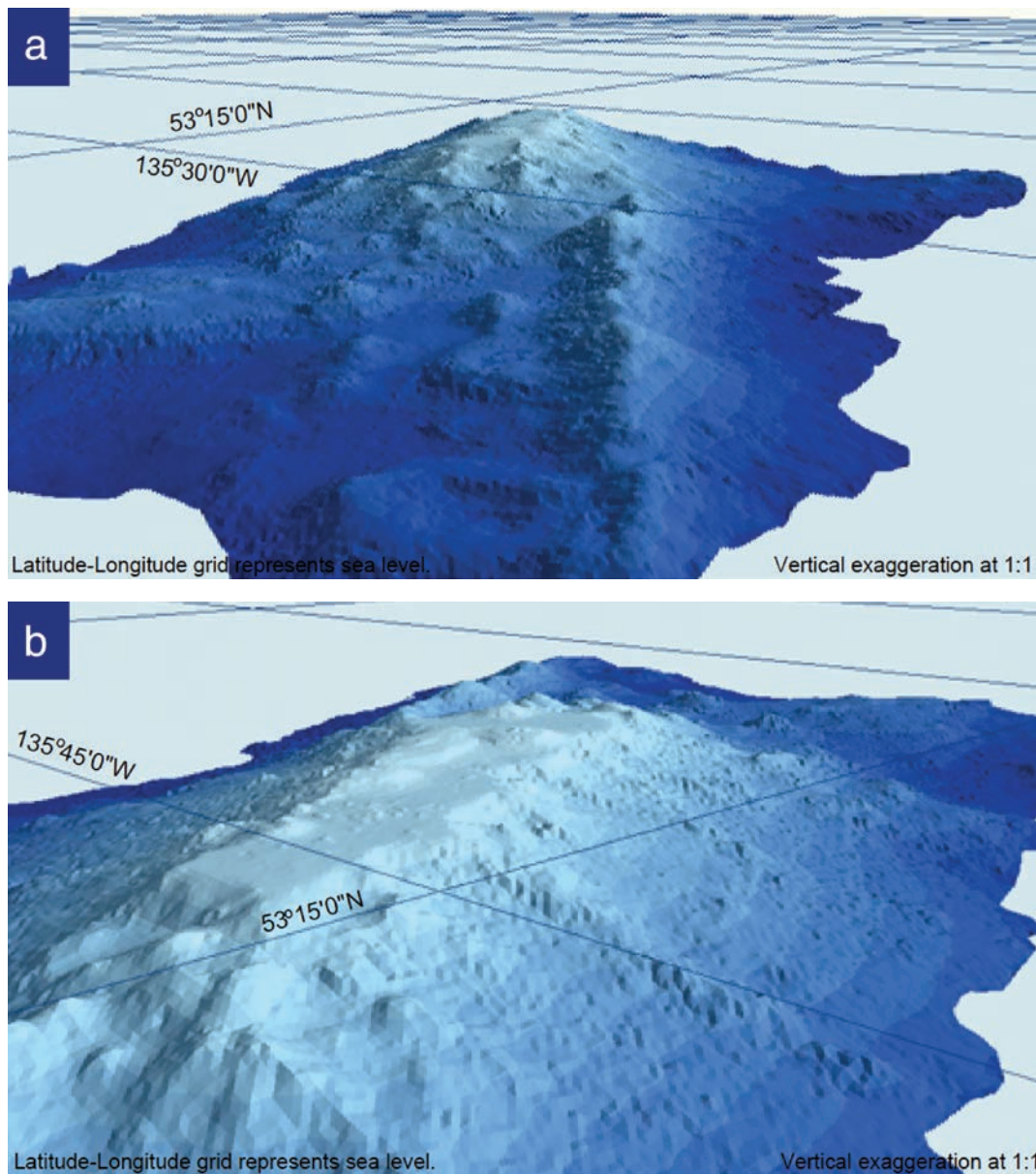


Figure 13.7. SGaan Kinghlas–Bowie Seamount perspective views (a) and (b) (after Canessa et al. [2003]).

By the authors, based on Canessa et al. (2003). Bathymetry data from the Canadian Hydrographic Service and US National Oceanic and Atmospheric Administration; bathymetry model from AXYS Environmental Consulting.

This section describes the development of a “proof of concept” marinescape geovisualization model of SGaan Kinghlas–Bowie Seamount to bridge the experiential and knowledge gaps concerning this remote MPA. The project aimed to enhance the 2.5D bathymetric model with photorealistic and geographically accurate marinescape geovisualizations. The model was viewed by individuals involved with SGaan Kinghlas–Bowie Seamount in a variety of capacities to acquire their feedback.

Data and Methods

Data and information were acquired from a variety of sources. The multibeam data that captured detailed depth was fundamental to the project. Multibeam data with 5 m resolution was available for the top 200 m of Bowie Seamount. Available georeferenced video and still photography enabled geographic understanding and mapping of habitats and species. Field data, species lists, and other observations and reports were used to additionally characterize oceanographic conditions, geological composition, and species assemblages.

The first step was to build a bathymetric model using the multibeam data in ArcGIS. Because of file size and processing time, 10 m resolution was used for a small area near the pinnacle. The bathymetric model is a good representation of the overall topography. However, use of that resolution results in a relatively smooth surface. Video and photographs, in fact, show a rugged and uneven surface composed of weakly cemented volcanic tephra and volcanic sand. The bathymetric model was imported into 3D Nature’s Visual Nature Studio (VNS), in which a surface that more realistically portrays ruggedness was created by modifying the terrain effect in the software using parameters such as fractal depth and vertical displacement. Color and pattern were also applied to simulate vegetation ground cover (figure 13.8a). Images of ground cover were extracted from video and photos and mosaicked to further enhance visual representation of actual benthic habitats (figure 13.8b).

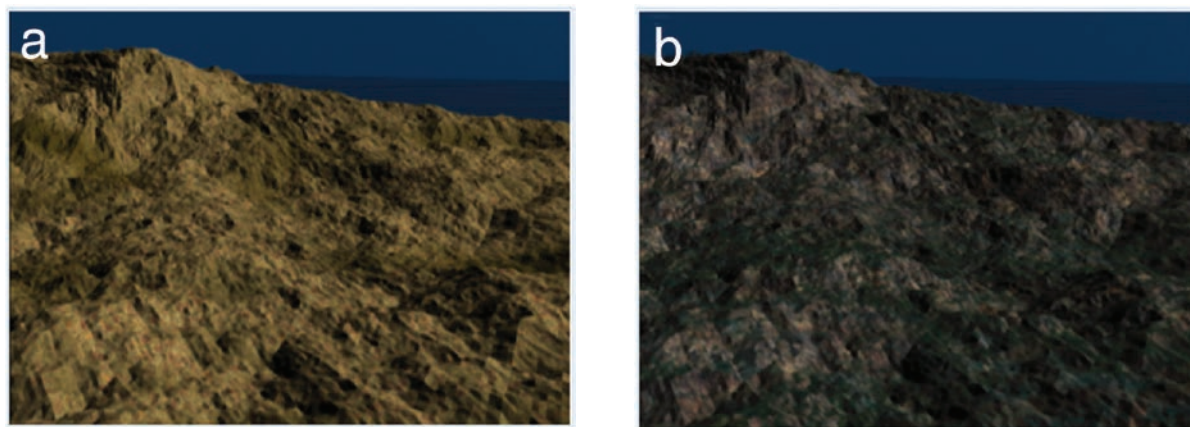


Figure 13.8. SGaan Kinghlas–Bowie Seamount substrate geovisualization in (a) simulation with pattern, size and color; and (b) a mosaic of images extracted from photos.

Once the bathymetry and substrate were modeled, attention turned to the water column and animal biota. Field reports described the water as clear and deep blue with a horizontal visibility of approximately 15 m. These conditions were simulated using atmospheric effects such as fog and haze (figure 13.9). The last step was to add species assemblages and individual organisms. The seamount ecosystem was divided into four ecotypes based on depth ranges of 0–30 m, 30–60 m, 60–200 m, and below 200 m. These ecotypes were defined based on the distribution of algal cover as described in field reports. Sufficient information was available to model all but the ecotype below 200 m. Each

ecotype was divided into overstory and understory to inform the vertical distribution of organisms. The understory contains small ground cover plants and benthic species. The overstory contains tall plants and pelagic organisms. In this proof of concept, only understory was modeled. Finally, species groups and individual species were identified from field reports and species lists. These designations were assigned to the appropriate ecotype to build a species library. Each species identified requires a graphic image of an individual organism so that it can be placed on the ground cover. Gradually, a species image library is created. The result is an interactive 3D model of the seamount pinnacle that can be rotated and viewed from different angles. A short dive-through video has been created of one path over the seamount. As the dive-through proceeds, the changing longitude, latitude, and depth (noted as camera elevation) is displayed, confirming that the seascape model is georeferenced. The marinescape visualization video is available in the book's online resources. For more information, see the "Supplemental Resources" section at the end of this chapter.

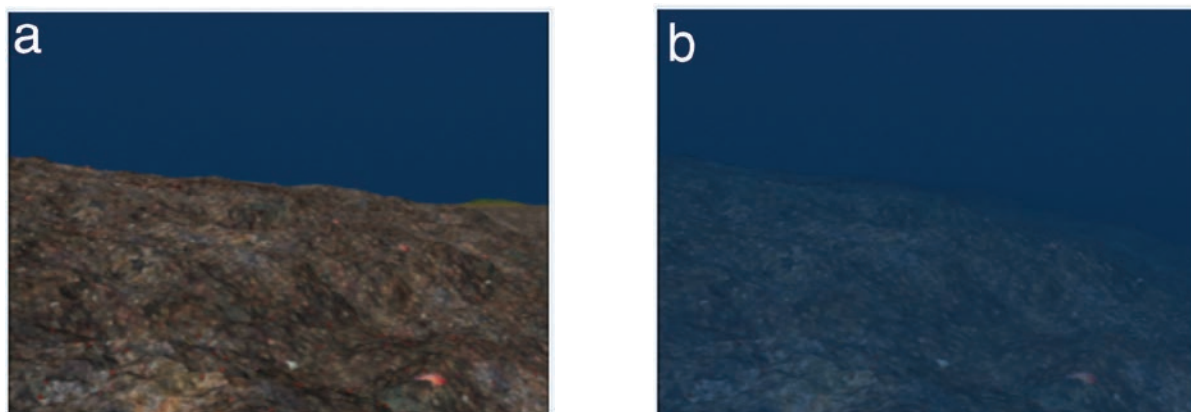


Figure 13.9. SGaan Kinghlas–Bowie Seamount simulation of visibility (a) without atmospheric effect and (b) with atmospheric effect (e.g., fog and haze).

Evaluation

The SGaan Kinghlas–Bowie Seamount proof of concept marine geovisualization was distributed to individuals engaged with SGaan Kinghlas–Bowie Seamount in varying capacities, such as biologists, planners, and members of the Advisory Board. Users were presented with an audiovisual description of the development of the model and a link to the dive-through video, which is also available in the book's online resources (see "Supplemental Resources" at the end of the chapter). Users then completed an evaluation survey.

Geovisualizations often must balance being informative, visually realistic, and spatially accurate, which can require trade-offs among the three. Respondents were asked to indicate the importance they placed on the need for maps and visualizations to be informative, realistic, and georeferenced. With respect to using maps and visualizations for planning and management of SGaan Kinghlas–Bowie Seamount, respondents said that being informative, realistic, and georeferenced were all important, although being informative was rated most important. With respect to using maps and visualizations for public education and outreach, respondents said that being informative and realistic were important but were relatively neutral on the importance of visualizations being georeferenced. On a scale of 1 to 5, from very unrealistic to very realistic, respondents rated the SGaan Kinghlas–Bowie Seamount proof of concept marine geovisualization a 4, somewhat realistic. On a scale of

1 to 4, from misinformative to very informative, respondents rated the SGaan Kinghlas–Bowie Seamount proof of concept marine geovisualization a 4, very informative.

Although this survey was not a comprehensive evaluation of the SGaan Kinghlas–Bowie Seamount proof of concept marine geovisualization, it provided some insight and direction, particularly with respect to the need for a more complete representation of the ecosystem, including the water column (e.g., near-surface currents, areas of upwelling, and high-productivity areas). On the other hand, all respondents acknowledged that the available data for SGaan Kinghlas–Bowie Seamount is critically limited. One respondent noted that field data must be collected with marinescape geovisualization in mind, as opposed to retroactively trying to generate marinescape geovisualization with whatever data is available. Several respondents noted the importance of validating the geographic accuracy and overall validity of the marinescape geovisualization model, without which it may serve to misinform rather than inform. One respondent also commented that the haze effect made the visualization blurry and difficult to see. This comment reflects the challenge of balancing realism and abstraction to create an effective and informative geovisualization. Despite some of these limitations, respondents noted a variety of applications for the marinescape geovisualization model, including

- to determine whether the distribution and relative abundance of apex predators (seabirds and marine mammals) within the vicinity of the seamount were predictable spatially/temporally;
- to address the impacts of commercial fisheries that have already occurred in order to model the predicted future impacts of fishing;
- to model the recovery of key habitat features;
- to interact with the area place markers for proposed/conducted activities (e.g., be able to turn on/off layers of track lines surveyed and instruments deployed);
- to identify an area proposed for certain kinds of activities and determine what is there as to the type of anticipated impact;
- to share with people using the area to inform them of areas that may be more or less sensitive to their activities (more effective/efficient planning of activities and review of proposals); and
- to engage the public.

Research and Development Agenda

This section highlights key issues in advancing marinescape geovisualization. It addresses both technological development and user-focused research.

Technological Development

3D Model Libraries

To fully represent the 3D marine environment beyond bathymetry requires that a bathymetric model be populated with 3D marine objects. Currently, urban and terrestrial environments are well represented in 3D GIS and virtual landscape environments. Landscape visualization software and some GIS software maintain their own library of 3D objects that can be imported into 3D scenes. These objects include, for example, city buildings, street features, terrain, and trees, which contribute to realistic renderings for urban and terrestrial planning (e.g., Esri CityEngine and VNS) (Fritsch and Kada 2004; Lloret et al. 2008; Yano et al. 2009). In addition, the Google SketchUp 3D Warehouse provides online access to a 3D object library for users to download and insert into a scene.

Google SketchUp's 3D Warehouse library includes 3D marine-related objects—in particular, coastal infrastructure and marine vessels; however, marine plant and benthic 3D models are nearly absent. A shared online library of 3D marine objects and substrate textures would facilitate the enhancement of marinescape geovisualizations.

Moving Objects

Although some of the objects discussed here are more or less static depending on the temporal scale (e.g., geological features), many objects on the seabed, in the water column, and on the sea surface are mobile. It is important, therefore, to model and represent the movement of such objects in a way that reflects their behavior. This modeling requires, for example, animation of a feature (e.g., ship, whale feeding, diurnal migration of zooplankton) moving along a path (Ware et al. 2006). More challenging is modeling the dynamic nature of wave movement and corresponding disturbance of sediment, or tidal movement. In this regard, computer game engines have more sophisticated animation capacity (Wang 2005) than traditional GIS or Google Earth. Perhaps, the next major advancements in coastal and marine geovisualizations could result from a similar type of partnership initiative, as seen with *Infinite Scuba*, involving collaboration between game designers, marine scientists, and GIS experts to model and visualize moving objects in the marine environment.

Modeling a Fluid Environment

Although some objects can move through their own capacity of mobility, other objects (e.g., suspended biota and materials) are moved by external forces (e.g., currents), which introduces an added complexity to modeling and visualizing movement or temporality. In both the Nereus and BP oil spill examples, temporal information was expressed only for singular variables, respectively fish stocks and oil spill patterns. However, in the case of the coastal and marine environments, highlighting a particular set of time-sensitive elements at the expense of obscuring others can help reveal the complexity and dynamism of these spaces. Therefore, the challenge for coastal and marine geovisualizations is to determine how to incorporate fourth-dimensional properties in a manner that comprehensively captures the unique interactions and relationships of marine elements and related terrestrial elements. A potential approach to meeting this challenge could be using game technology.

Game engines provide the ability to visually capture the physics of marine features and simulate their movements and interaction with other marine objects in underwater environments. Forces, such as friction, torque, gravity, and mass-based interaction of marine features, can be realistically simulated by inputting modeled equations into the game engines (Gladstone 2011). A commercial software named Unity 3d has the ability to display spatial data in 4D and uses a physics engine named Nvidia PhysX, developed for visualization in physics. Examples of physics variables include mass, drag, angular drag, gravity, and simulation of particle systems. However, modeling the physics of a fluid and of each object in the marine environment can be computationally intensive (Gladstone 2011; Casas et al. 2012). For example, modeling a boat on water requires weight, buoyancy, air friction, water friction, and propulsion (Casas et al. 2012). Another study attempts to model swimming behavior of virtual creatures by using buoyancy and water drag computations (Nakamura et al. 2011). Some of these calculations can be computationally intensive, but oversimplifying physics parameters decreases realism; therefore, trade-offs are weighed to determine which parameters are most useful for simulating the environment (Nakamura et al. 2011; Casas et al. 2012).

Users and Usability

The previous section focused on research directions in the technical/computational development of 4D marine visualization. This section addresses user-focused research.

Interactivity and Immersion

Germanchis and colleagues (2004, 90) argue that “virtual reality technology produces a more complete perceptual experience than traditional (carto)graphic representations.” Interactivity and immersion enhance that perceptual experience. This technology is particularly important for marinescape geovisualization as real-world experiences by users may be limited to activities such as snorkeling and diving. As such, most marinescape geovisualization users bring only secondhand experiences of the marine environment, acquired through films, photographs, and books.

Interactivity and immersion take the perspective of the user into account in the visualization scene.

Interactivity reflects the way the user directs the navigation and exploration of the scene. Interactivity might allow users to manipulate the perspective view, interrogate features, or modify elements of the scene. The way in which interaction occurs can be thought of as interaction metaphors (MacEachren et al. 1999; Germanchis et al. 2004). Current interaction with marine spatial data and marine geovisualizations is based on the same metaphors we use for terrestrial and urban environments. New interaction metaphors may be required for marine environments, especially when emphasizing a sense of immersion (Germanchis et al. 2004). For example, under a marinescape geovisualization for coastal planning, a user could interact with the data through a stakeholder metaphor, decision-maker metaphor, or scientist metaphor so that the environment and information are structured around the type of metaphor chosen, which in turn dictates the user’s interaction.

Immersion takes into account the perspective of the user in the visualization scene by embedding the user directly in the scene as a participant or avatar or providing the view through the eyes of the user. In terrestrial visualization, this may be a person who is walking, running, driving, or flying through a scene. The marine analogues are floating, swimming, diving, or driving a remotely operated vehicle (ROV). That immersive experience can be further enhanced by accentuating the entry into the marine environment (e.g., walking across the coast from land to sea or jumping in from a boat).

User Needs Assessment

A critical step in the advancement of marinescape geovisualization is ensuring that the development of such models and tools is tightly tuned to the needs of intended users. Scientists, marine planners, and the general public likely have different needs on a range of factors, including level of realism, amount and type of information, spatial accuracy, immersion, interactivity, and collaboration, to name a few. A user-needs assessment early in the process should address these and other key factors. Considering that marinescape geovisualization is novel, a user-needs assessment may require a prototype being developed for users to begin to understand and imagine how marinescape geovisualization might be applied to achieve their goals. Questions in a user-needs assessment might include

- Who are the intended users?
- What is their level of knowledge of the marine area and key issues?
- How much marine experience do users have?
- What types of visualizations have they used previously for the study area?
- How important is realism?

- How important is information?
- How important is spatial accuracy?
- Is the focus on the sea surface, water column, seabed, or below the seabed?
- How important is object movement and the fluidity of the surrounding environment?
- How important is it for users to feel that they are immersed in the scene?
- What extent of interactivity and self-direction in the scene is required?
- Is the marinescape geovisualization to be primarily used for viewing or analysis?
- Is the visualization to be used by an individual or collaboratively in a group?

With respect to the last question, a growing body of research exists on geovisualization for collaborative use of map-based visualizations in groups (Brewer et al. 2000; MacEachren 2004). A number of case studies in terrestrial and urban environments discuss collaborative uses of 3D GIS and the geovirtual environment (Stock et al 2005); but few, such as COVE discussed earlier, exist for marine contexts. Collaborative uses of GIS for marine spatial planning are still confined to 2D GIS case studies (Alexander et al. 2012; Merrifield et al. 2013). 3D visualizations for marine spatial planning contexts are dominated by static 3D landscape visualization software (Shaw et al. 2009; Phadke 2010), rather than navigable 3D GIS or game engines.

Usability, Evaluation, and Effectiveness

Finally, as marine geovisualization advances, we must empirically evaluate both its usability and effectiveness in achieving its case-specific goal (Jude 2008). Ultimately, we are interested in answering questions such as:

- Is the available data adequate for an effective marinescape geovisualization?
- Is it important to communicate the difference between simulation and reality, or the level of uncertainty in the data, to the user?
- Was information intensity a barrier?
- Did some elements create more of a distraction than a focus?
- To what extent did the marinescape geovisualization
 - provide insight that was otherwise missing from other available data, information, or visualizations?
 - facilitate planning and management decisions?
 - create a connection to place?
 - engage the public?
- What limitations did users face?

Conclusion

Marinescape geovisualization offers an exciting medium to enhance our connection to the marine environment and ability to make more informed decisions that reflect its spatiotemporal dimensions. Advances in landscape visualization offer a starting point (e.g., simulating turbidity with fog and haze and creating 3D object libraries). However, the comparatively limited amount of georeferenced marine data and the integral 3D dimensionality, along with the fluidity of the water column, require more sophisticated techniques such as those used in game engines. Thus, we are heading toward an integration of standard practices in landscape visualization with the innovation of game engines for virtual reality using GIS for geographically accurate place-based visualizations. However, we do not want to lose the geographic connection to marine visualization that may result with an emphasis

on game engines. Geography in general can have a unique impact on the use of computer-game research by bringing the real world into these simulations. In addition, GIS can greatly benefit from the enhanced interactivity and immersion of game engines. In addition, we must not lose sight that the aim is not to develop marinescape geovisualization for the “wow” factor. Instead, the primary goals are, arguably, to make more informed planning and management decisions and enhance marine literacy among the public. Therefore, technological advancement should be complemented with research to understand how users engage with marinescape geovisualization and the impact that the marinescape geovisualization has on meeting the users’ goals.

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Supplemental Resources

Dawn J. Wright, ed.; 2016; *Ocean Solutions, Earth Solutions*, second edition; http://dx.doi.org/10.17128/9781589484603_13d

The digital content for this chapter, listed below in this section, can be found in the book's online resources (esri.com/esripress-resources/ocean-solutions-2e).

Geovisualization Videos

Two geovisualization videos can be viewed online:

- *Explorations in Marinescape GeoVisualization*
- *“Dive-Through” of a Geovisualization Model of the Pinnacle of SGaan Kinghlas–Bowie Seamount*

CHAPTER 14

Approaches to Visualizing Complex Ocean Data Using Worldwide Telescope

Rob Fatland

Abstract

Trends in oceanography toward burgeoning model complexity and resolution, profusion of sensor platforms and instruments, expanding remote-sensing products, and new data-intensive analytical laboratory methods are outstripping scientists' ability to keep pace with their own data. Advances in visualization methods based on the Worldwide Telescope virtual globe can help narrow the gap between data acquisition and data insight. Three data visualization scenarios from oceanographic research are described, all motivated by current research on marine microbial ecology in relation to dissolved organic matter and physical transport processes. The role of visualization is placed in the broader context of data analysis and data management, with the accompanying suggestion that both data services and resource confederation are important supporting philosophies, and heterogeneous data resources are amenable to a complementary-tools approach that includes GIS. The data visualization scenarios described here use the Worldwide Telescope capacity for large (on the order of 10 million data values) time-series datasets, together with three-dimensional spatial rendering and elapsing time, to create data exploration environments. Results of this work include implementation of a curtain plot as a data selection tool and visualization controller for Worldwide Telescope, the potential for experimental design based on estuary model output, and the identification of new ideas for the deconstruction of dissolved organic matter spectra.

Introduction

A challenge of oceanographic research data is that research programs are increasingly able to collect many different types of data with the idea of arriving at new insights; but the tools for organizing, analyzing, comparing, and understanding these datasets lag behind and hinder that path to insight.

This chapter describes oceanographic research visualization methods that incorporate time and accommodate trends in complex data. This methodology also extends to considerations of data analysis and data management in relation to visualization and, more broadly, in relating research questions to data.

Although oceanographic datasets occupy a vast conceptual space, this chapter keeps to a modest length by briefly considering data visualization in three illustrative scenarios. To address these scenarios, I describe methods developed using the Worldwide Telescope (WWT) visualization engine, a freely available virtual globe that supports large (~10 million-element) datasets and time-series playback. I also present three broader ideas suggested by the relationship between data visualization, analysis, and data management: (1) heterogeneous data resources are amenable to a multiple-pillar or complementary-tools approach that includes GIS, virtual globes, and graphing tools; (2) a data-as-a-service technical philosophy can be a viable complement to the more traditional method of downloading the data to a local computer system; and (3) research as a process is hindered by delays, by various forms of latency at many time scales, from seconds to years, and this state of affairs can be significantly improved by learning, developing, and applying emerging technology. These remarks are inspired by the book *The Fourth Paradigm* (Hey et al. 2009), which presents a deeper look at data-intensive science and the gaps in converting the capacity to gather increasing volumes of data into scientific insight.

The three example visualization scenarios described in this chapter are motivated by research on marine microbial ecology in relation to dissolved organic matter (DOM) and physical transport processes. Microbial ecology in the physical ocean is studied by the Monterey Bay Aquarium Research Institute (MBARI) and collaborators, particularly through synthesis of observational time-series datasets such as those produced by conductivity-temperature-depth (CTD) in situ observations, metagenomic/metabolomic methods (in situ and laboratory), remote sensing of sea surface state, acoustic Doppler current profiler (ADCP) measurements of local currents, in situ fluorescence, backscatter and nutrient observations, and so forth (e.g., MBARI 2010; Das et al. 2011). The water transport example described here is based on the Regional Ocean Modeling System (ROMS) (Arango and Shchepetkin 2014) computational fluid dynamics model applied to estuaries, particularly in work done at the University of Washington (e.g., Geyer and MacCready 2014). DOM research includes in particular spectral analysis of DOM as carried out at the Old Dominion University and collaborating institutions, herein with particular emphasis on the technique of Fourier Transform Ion Cyclotron Resonance Mass Spectrometry (commonly abbreviated FTMS) (Sleighter and Hatcher 2007). In the resulting visualization scenarios, I suggest a research question that is addressable in some measure through visualization and then present approaches to visualization developed using WWT. WWT is a free graphics processing unit (GPU)-powered virtual globe (Microsoft Research 2014b) that runs on the Windows operating system. WWT and associated geoscience tools, collectively called Layerscape (Microsoft Research 2014a), are provided by Microsoft Research as research and education tools for general use.

This chapter seeks to describe a research-to-data relationship framework, and then to describe three notional experiments A, B, and C and the visualization methods developed to address them.

- Experiment A: the Environmental Sample Processor (ESP) built and operated by MBARI is allowed to drift for five days along the continental shelf off Monterey Bay. This drift experiment is further supported by a robotic autonomous underwater vehicle (AUV), an ADCP, and other sensors and platforms. Research question: Does ADCP data provide a usable constraint on autochthony/allochthony estimation of water measured by drifting sensors?

- Experiment B: a computational fluid dynamics model is driven by observational data to produce a 72-hour forecast of water conditions across a three-dimensional (3D) grid. Derived parameters include temperature, pH, dissolved oxygen, and phytoplankton and zooplankton concentration estimates. Research question: Can this fluid dynamics model suggest an in situ validation-observing campaign?
- Experiment C: analysis of DOM using FTMS. Research question: Can animated visualization, specifically extension of traditional two-dimensional (2D) graphs into three and four dimensions, suggest relationships in FTMS molecular formula sets?

A Research-to-Data Relationship Framework

A model of dynamic oceans can be assembled beginning with a static structure and adding dynamism (for example, currents as a set of smoothly moving conveyor belts, seasonal variability, turbulence, Coriolis effects, tides, atmospheric and bathymetric coupling, estuarine input, and so forth). This assembly is often presented by means of flat diagrams, maps, graphs, and equations on a static page, but we now have the means to bring the oceans to life through computer graphics and animation. Computer-enabled dynamism is an expanding discipline in oceanography research that offers a complementary enhancement to traditional approaches. To expand briefly beyond the topic of strict visualization, I present a three-component framework (figure 14.1). The first component is a hierarchy of models, questions, and problems in research that can be said to represent the state of scientific understanding of the oceans in earth system science. Placed opposite the research is the topic of data, particularly as a multiplicity of sources that are both complex and time varying. Research and data are then linked by processes: analysis, visualization, and data management. This framework is intended to indicate that challenges in data visualization exist not in isolation, but in the context of analysis and data management.

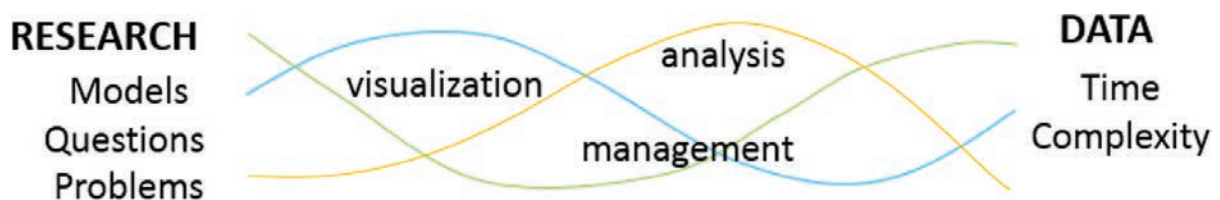


Figure 14.1. A research framework, in which research questions are connected to data complexity in terms of interrelated visualization, analysis, and data management processes.

Latency hinders progress in research on different time scales, from a user interface that introduces a few seconds of delay (perhaps discouraging data exploration) to an arduous validation process that slows data publication and reuse for years. If a data resource can provide several hundred datasets of interest but each requires 30 actions (cursor drags, clicks, text entries, and so forth) to make the datasets readable in a graphing application, two questions typically arise: “Is there a way to automate this process?” and “How many of these files are really essential to analyze?” In other words, latency can divert time and energy, and it can alter the course of inquiry. Opportunities exist to develop technical solutions for various latencies across analysis, visualization, and data management. I describe one of these briefly, to wit, data services, and the related idea of confederating visualization and analysis applications.

Data Services and Monolithic versus Confederated Visualization Environments

Data as a Service (DaaS) is a developing alternative to working with local (“on this computer”) copies of data. DaaS means that datasets are provided as an on-demand resource rather than as files saved on a local storage device such as a hard drive, with an early example as the Open-source Project for a Network Data Access Protocol (OPeNDAP) (2014). More recent technologies such as the Open Data Protocol (OData) (OPeNDAP 2014); web map services (WMS) (Open Geospatial Consortium 2014); and the ArcGIS Online service, which combines both DaaS and Software as a Service (SaaS), contribute to a growing pool of solution templates. Many of these developments are reflected in the charter of the National Science Foundation–funded Data Observation Network for Earth (2014) to support “new innovative environmental science through a distributed framework and sustainable cyberinfrastructure.”

The historical practice of manipulating local discrete files is typically quick and easy to understand, provided that the datasets are neither too numerous nor too large. A negative aspect of local data management arises when data volume and/or complexity increases. Files must be identified, opened, read, modified, saved, closed, copied, and renamed, often in a rigid (possibly brittle) manner. This workflow suggests a horizon of complexity in which datasets become too complex to be reliably managed as local files. This horizon leads to remote access (DaaS), database implementations, machine-independent formats such as network Common Data Format (netCDF) (Rew and Davis 1990), migration of computational tools to the cloud, and other SaaS approaches (e.g., ArcGIS Online, at arcgis.com). DaaS, of course, is not a panacea, introducing its own form of potential latency through its dependency on consistent, fast responses from remote computers and on the Internet in general. At this time, DaaS can be seen, therefore, as a complementary, rather than substitutive, means of obtaining data, with the following positive attributes:

- Datasets can be fetched as desired subsets rather than en masse.
- Datasets can be locally abandoned, rather than saved and curated, and refetched as needed.
- Datasets can be queried and fetched programmatically.
- Datasets can be updated by the DaaS provider, together with version metadata.

DaaS suggests an expanded approach to data visualization and analysis, to wit, confederation. Once a heterogeneous ensemble of data becomes available, a corresponding ensemble of analysis and visualization tools can be connected to it and to one another. Traditional visualization environments follow the rule of “begin by loading a dataset.” A single application reads data in a predetermined format, often provides for some configuration steps, and then presents a graphical representation of the data. Built-in configuration controls such as a color map editor, scale exaggeration control, marker symbol menus, and filters then support the iterative exploration of the data in that application. Such monolithic software anticipates and implements as many useful data views as possible. Examples include the Collaborative Ocean Visualization Environment (COVE) (Center for Environmental Visualization 2014), older versions of Microsoft Excel, and the venerated Generic Mapping Tools (GMT) (Wessel and Smith 1991). In contrast, a confederated visualization/analysis environment (figure 14.2) provides DaaS pathways for data import and distributes visualization and analysis tasks across a number of applications.

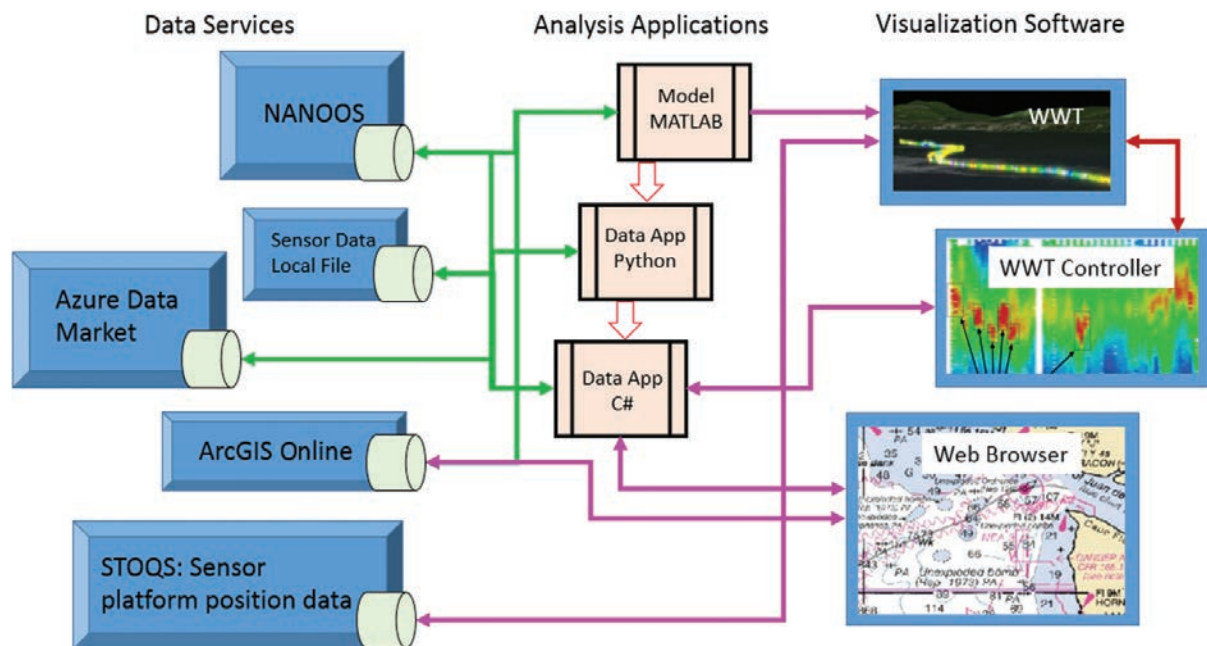


Figure 14.2. A confederated approach to data analysis and visualization: Data as a Service is represented as several source blocks (left, in blue) with data access ports, as well as ArcGIS Online as both Data as a Service and Software as a Service. NANOOS is the Northwest Association of Networked Ocean Observing Systems. STOQS is Spatial Temporal Oceanographic Query System. Analytical and visualization software treat these datasets (including local files) as on-demand resources. Domain expertise is built into the analysis applications. The WWT Controller (right, center) is described further in figure 14.5. Author illustration; map image courtesy of NOAA.

Software development in a data service environment can become modular in nature. Data to be provided as a service can be systematically prepared for use, in which “data preparation” is an umbrella term for quality assurance, gap filling, coordinate and time transformation, provision of descriptive ancillary information, format standardization, and so forth. Data preparation by the service provider is abstracted from data use (analysis and visualization) by the researcher. The researcher, in turn, may develop software that fetches prepared data from multiple services and builds synthetic new services. As an example, suppose a computational fluid dynamics model for an estuary requires source data from stream gauges as well as tidal, wind, and precipitation forecast data. An intermediary program can tap appropriate DaaS resources and synthesize a data service to drive the estuary model without having to modify the model code itself. This modularization is a step toward making it easier to implement the model for many estuaries.

Visualization engines that are a component of a confederated environment do not need to do “everything,” as in all possible visualizations, plus analytics. In the research examples that follow, visualizations developed in WWT use its native primitives: markers, lines, raster images, geographic coordinates, and time. WWT supports basic geographic, geometric, and temporal information (latitude; longitude; elevation; depth; x, y, z; date; time; time-elapse rate), in addition to a free viewing perspective. It provides graphical attributes for raster images, lines, polygons, and points; specifically, color, opacity, brightness, and time persistence. Hence, in this work, WWT renders, but does not manipulate, data. It does not calculate running averages or produce new color maps or create filtered views. Instead, a separate confederated application performs these tasks and sends WWT preconfigured representations of the data. A separate application of this type is unconstrained in terms of how it is built. It may, for example, be Matrix Library (MATLAB) code; Microsoft Excel pulling data from a SQL Server database; a Python script; a C# application built on the WWT

developer library Narwhal; or ArcGIS software that is run on the desktop, in the new ArcGIS Pro application that is part of ArcGIS for Desktop (Glennon 2014), or in the cloud in ArcGIS Online. Decoupling domain knowledge, data preparation, programming métier, and data visualization serves to separate tool building from the research process.

Two desiderata follow from latency minimization: first, a useful visualization can suggest a hypothesis that is amenable to testing through analysis. It is consequently desirable to build analytical tools that can easily identify or latch onto data subsets of interest. Second, it is desirable to build interface controls that allow quick editing of visual presentation: for example, turning graphical elements on and off, increasing transparency, exaggerating spatial dimension, and so forth. This narrative now turns to the three visualization examples of interest with some inherited context from these prefatory remarks.

Experiment A: A Five-Day Marine Drift Experiment

Experiment A is a drift experiment carried out by MBARI and collaborators in the fall of 2012 off the coast of Monterey Bay. This experiment is one in a series under the rubric of the Controlled Agile and Novel Observing Network (CANON) (MBARI 2010; Das et al. 2011). A central objective of the experiment is to drift with prevailing currents, remaining within a coherent water mass and observing microbial populations and metabolic processes over the course of several days. In practice, it is readily acknowledged that the central drifting platform, ESP (MBARI 2013), is subject to both depth-varying ocean currents and winds that act on the ESP surface float, and hence may move from one water mass to another, or from one microbial ecosystem to another, over the course of the experiment. In consequence, a view of the experiment centered on ESP as it drifts is called quasi-Lagrangian (Price 2006).

An ideal time-series picture of the water volume surrounding ESP would be synoptic (i.e., representing a comprehensive picture of the state of the system over time). MBARI researchers place many sensors in the water toward producing such a synoptic view, particularly by tasking a long-range AUV to orbit ESP once every three hours at a radius of approximately 1 km while continuously diving to 100 m and returning to the surface. Figure 14.3 shows the resulting orbiting/porpoising AUV trajectory that surrounds the stately drift trajectory of ESP.

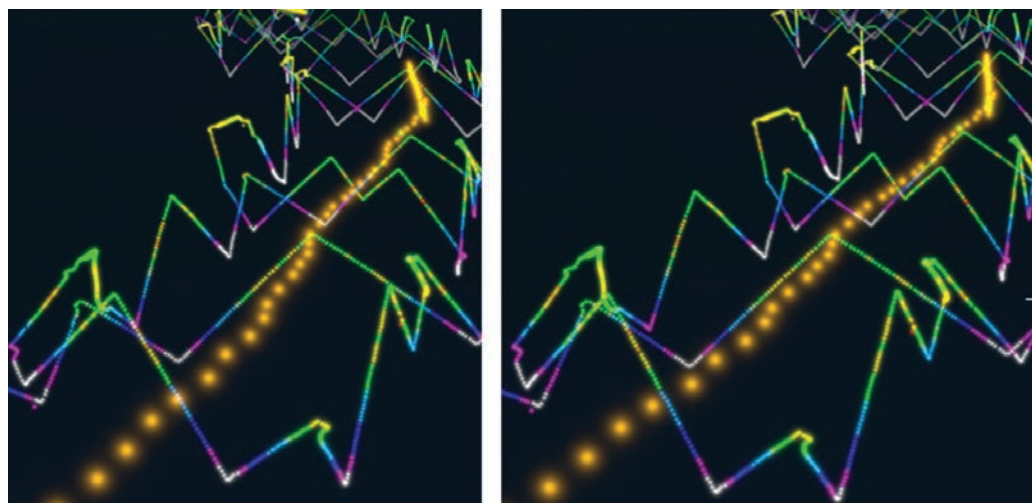


Figure 14.3. Experiment A, excerpted from the Worldwide Telescope visualization engine. Uncrossed stereo view of the Environmental Sample Processor track (orange) in relation to the path followed by an autonomous underwater vehicle in a Monterey Bay Aquarium Research Institute Controlled Agile and Novel Observing Network drift experiment. The underwater vehicle track shows nitrate concentration encoded by color.

Using WWT to view the time evolution of these different trajectories, it becomes clear that the datasets are difficult to compare visually. Although both the AUV and ESP carry CTD sensors, the porpoising path of the AUV contrasts with the relatively fixed depth of ESP. Taking an assumption of a stratified water column, I created a visualization (figure 14.4) in which ESP and AUV measurements are emphasized and made comparable using radiating horizontal ripples. AUV ripples can be triggered (as in figure 14.4) by a particular depth, or they can be triggered by a range of sensor measurements X . The latter case produces a visual approximation of surface (or volume) of constant X , whereas the former case allows the researcher to visually compare sensor measurements between platforms, AUV to ESP.

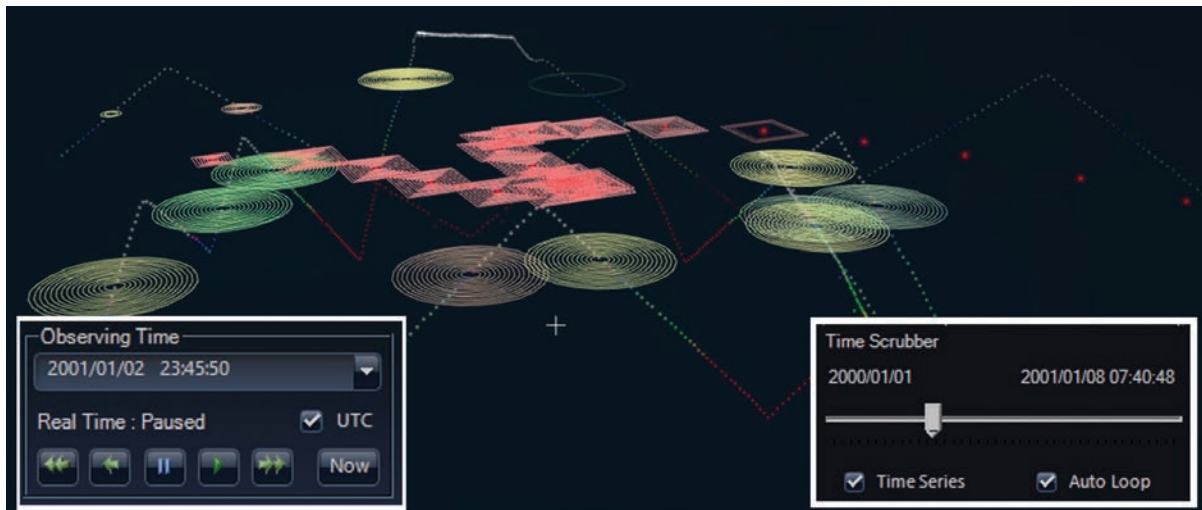


Figure 14.4. Experiment A, excerpted views of Worldwide Telescope. This is a volume-filling representation of a stratified water column, showing an autonomous underwater vehicle path (zigzag) in relation to the Environmental Sample Processor drift path (red dots, center right). Concentric rings show measurements made by corresponding instruments (in this case, salinity). Insets are the Worldwide Telescope internal clock (lower left) and time slider (lower right). The drag handle on the time slider allows the researcher to move the Worldwide Telescope clock and corresponding data view backward and forward in time.

ESP consists of a surface float and an in situ biological laboratory that is suspended at a depth of 10 m, together with a CTD component as noted. The surface float mounts a downward-looking ADCP that continuously measures relative lateral currents at 2 m intervals, from the surface to a depth of 90 m. If this lateral flow is fairly uniform and time-invariant for a period of time, it might be a suitable proxy for the current flow nearby, particularly at the location of the AUV. This relationship, in turn, suggests that the orbiting AUV might sample the same water twice, once on an initial pass and again later as its orbit actively moves it to where the water is passively advected by relative lateral currents. This idea suggests a Lagrangian evaluation through visualization and analysis. To what extent is this drift experiment truly Lagrangian? That is, is the drifting ESP staying within a self-consistent water mass; or if not, how gradually does it move from one water mass to another, with a distinctly different recent history? The question can be addressed by using ADCP measurements to advect AUV positions with time. The AUV itself is not advected, but the water through which it passes is advected. Figure 14.5 shows a confederated approach to visualizing this idea. A graph called a *curtain plot* is created by software that is independent of WWT. This graph shows time and depth (horizontal and vertical axes, respectively) for the AUV time-series data. Chlorophyll concentration measurements are represented using a heat map, with red representing the greatest concentration. Note that the time range spans five days and that the porpoising trajectory of the AUV is compressed

in this time period to give a visual impression of continuous measurement at all depths. The graph shows isolated areas of high concentration in the first two days, which then consolidate and migrate upward into a chlorophyll lens in the upper 20 m of the water column in the latter part of the drift interval.

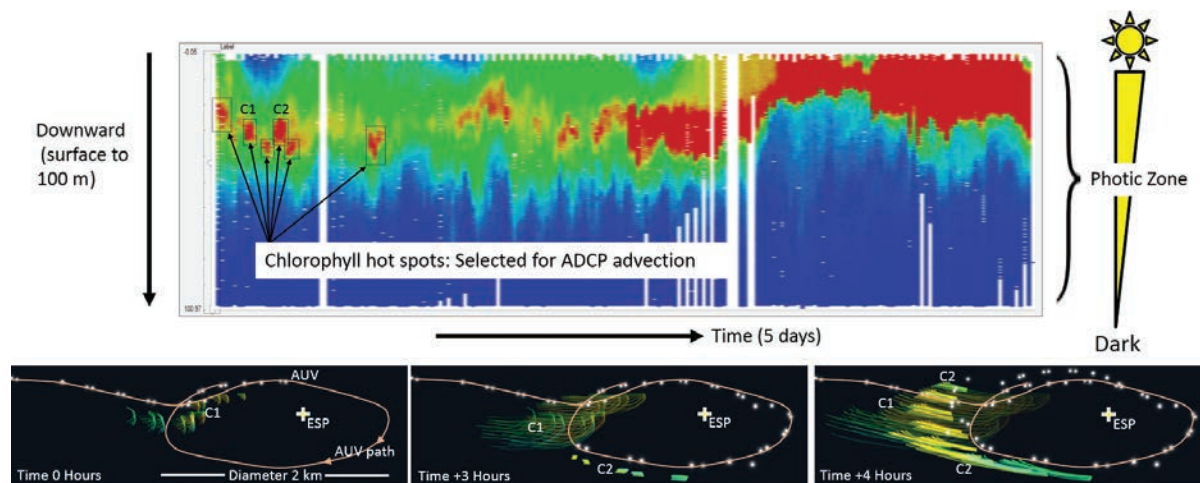


Figure 14.5. Experiment A, a graph (aka *chart*) control for Worldwide Telescope, from the Monterey Bay Aquarium Research Institute Controlled Agile and Novel Observing Network 2012 drift experiment. The time-depth curtain plot represents five days of Environmental Sample Processor drift, in which color indicates chlorophyll concentration with depth (red is maximum) as measured by an autonomous underwater vehicle orbiting the sample processor. Hence, this dataset folds back on itself in the Lagrangian frame as the underwater vehicle orbits the processor. The chart is a Worldwide Telescope control in two ways. First, a left-click cursor touch on the chart sets the Worldwide Telescope clock, so that a cursor drag across the chart is equivalent to dragging the telescope time slider. Second, a right-click cursor drag selects a region of the curtain plot as shown in the black boxes at the upper left. An acoustic Doppler current profiler mounted facing downward on the sample processor float measures lateral current relative to the sample processor from the surface down to 100 m. In consequence, a selected data block from the chart control can be advected in time, presuming it follows the same current as measured at the sample processor (i.e., at the center of the autonomous underwater vehicle orbit). In the first Worldwide Telescope frame, the underwater vehicle has approached from the left (white dots), and some of the data (faint color chevrons, selected as C1 in the chart control) has begun to advect. Upon completing the first orbit (upper middle frame), a second block of data, C2, has been selected (brighter color patches) and also begins to advect. The fact that C1 and C2 are spatially coincident under this advection scheme, combined with the underwater vehicle location with time, suggests that the underwater vehicle is moving through a coherent water mass with a locally high concentration of chlorophyll.

The curtain plot connects to WWT through an application programming interface (API), described in more detail as follows. This connection allows the plot to be used as a data selector. Clicking and dragging over an area of interest in the curtain plot extracts that data subset from the complete AUV dataset. This subset is advected using the ADCP current measurements as a proxy. The results are installed in WWT as a visualization layer. The lower part of figure 14.5 shows two such selections from near the start of the drift experiment. Both their location and advection suggest that two high-concentration chlorophyll signals in the AUV curtain plot may be part of the same water mass.

A confederated (broad) approach to the Lagrangian evaluation problem extends beyond the in situ sensor work described here. Availability of remote-sensing data for near-surface chlorophyll concentration, sea surface temperature, wind, and currents means that a GIS would provide an

independent approach to characterizing the Lagrangian fidelity of the ESP trajectory. Note also that the number of sensors (across platforms and sensor types) exceeds 100 in the 2012 CANON experiment, creating a considerable data management challenge. MBARI researchers have implemented the Spatial Temporal Oceanographic Query System (STOQS) (MBARI 2014) to carry forward their ongoing effort to provide data in the DaaS paradigm.

Data-to-Visualization Mapping

Before proceeding with experiments B and C, I describe mapping the time-series ocean data to visualization in a many-to-one sense; that is, from many types of oceanographic data to visualization in the virtual globe WWT engine. Relevant capabilities of the WWT engine include

- Métier: three spatial dimensions and supporting Cartesian and rectilinear coordinate systems
- Time support: date, time, time elapse rate, a time slider control, time looping
- User-controlled viewing perspective
- Support for 3D models and mesh surface rendering
- Blank canvas space that is free of geospatial context markers
- Raster/vector/point rendering support
 - Raster draping
 - Segmented lines, polygons
 - Point rendering with multiple marker options
 - Control of color, opacity, and (for markers) brightness
- GPU-dependent data capacity (one million to 30 million data points)
 - Comparatively large data capacity, enabling particle trajectory interpolation (i.e., continuous visual paths for individual entities)
- Reproducible perspectives and perspective sequence capture for storytelling
- Text, image, and audio annotation embedding
- A peer-to-peer API for automated configuration and data import
- Web service connectivity to data sources (WMS, OData)
- Cut-and-paste data table input
 - Columns that enumerate data attributes; rows that correspond to data values

In experiment A, the datasets include many types of measurement that are made along the AUV platform trajectory. Here, the basic CTD has been enhanced using additional sensors to measure fluorescence, dissolved oxygen, pH, and other parameters. A single marker can color-encode one type of measurement—say, salinity—but what of the other measurement types? Each type may be mapped to a structure such as a cube (12 edges and eight vertices) that translates with time tracking of the AUV location. This symbolization, however, presents the difficulty of remembering what each component of the structure corresponds to, in turn suggesting toggle switches for simplifying the view. Such a construction would require practice on the part of the researcher to use and interpret, an open topic. This example of using representational visual structures has an additional implicit degree of freedom, in marker decay time. As the AUV platform moves in space and time, the corresponding measurements are rendered in place; and a global time decay determines how long (on the WWT clock) that representation persists before fading out. Long persistence times tend to appear as long tails, suggesting a more spatially extended picture of the water volume. A short decay time also has an advantage, reducing visual clutter when many data streams are playing out in proximity. Similarly, opacity can be reduced to cut down on visual clutter. In some instances, a very faint, static monochrome view of a trajectory can be placed underneath a brighter dynamic view to provide a reference without obscuring the data/trajectory playback.

The WWT feature list cited here includes a time slider, as shown in figure 14.4. This configuration reflects a current time within an active (looping) time range and can be dragged to a moment of interest. This element, in combination with duration settings, gives the scientist a “browse through time” capability. Although WWT does not have an active data filter, the time control may be manipulated to provide that function as follows. A particular measurement type is mapped into a numerical time range, which is then declared to be time in the WWT table configuration for this data layer. By mapping data values to pseudotime in this way, the WWT time slider behaves as a data-windowing filter. For example, an AUV CTD time series for salinity in the range of 33.2 to 33.8 practical salinity units (psu) can be mapped to a time range from March 1 to March 31. The time slider setting now selects and illuminates locations in which the salinity measurement falls within a narrow range, showing all such points simultaneously, irrespective of when those measurements were made.

Experiment B: Computational Fluid Dynamics Model

ROMS produces a time series of ocean state cells, in which state includes the flow field, water temperature, salinity, pH, dissolved oxygen, chlorophyll concentration, and other parameters (Arango and Shchepetkin 2014). Figure 14.6 shows an oblique view of the continental shelf west of the Strait of Juan de Fuca, where the ROMS model was used to produce a flow field (Sutherland et al. 2011). A visualization in WWT was produced to explore the idea that coastal upwelling provides nutrient-rich water to Puget Sound, Washington, via Juan de Fuca Canyon. Point markers are placed at selected locations within the model volume and allowed to circulate according to the derived flow field, with an additive random walk component mediated by local estimated turbulence. The resulting particle trajectories are interpolated and imported as tracer data in WWT.

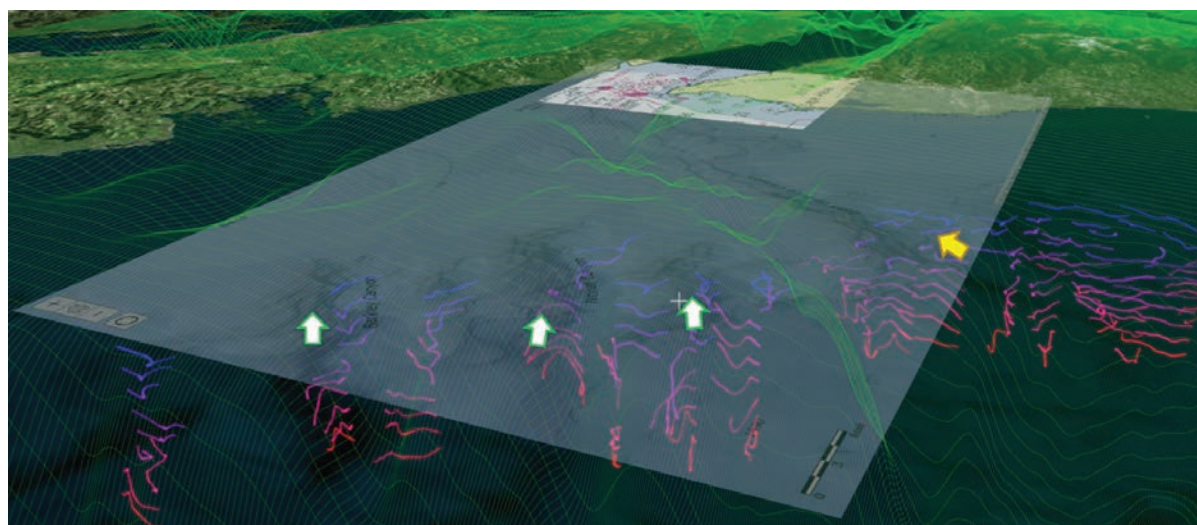


Figure 14.6. Experiment B, excerpted from the Worldwide Telescope visualization engine. The Regional Ocean Modeling System computational fluid dynamics model produces a time-varying vector field. Tracers placed and advected within the solution field show upwelling water entering the Strait of Juan de Fuca along Juan de Fuca Canyon (yellow arrow) and possibly from three other nearby canyons (white arrows).

Author illustration; map image courtesy of NOAA.

As a candidate research insight question: How might the ROMS model results suggest a validating experiment in the field? The WWT visualization shows not only flow up the Juan de Fuca Canyon, but additionally tracers that flow up two of three nearby canyons (figure 14.7).

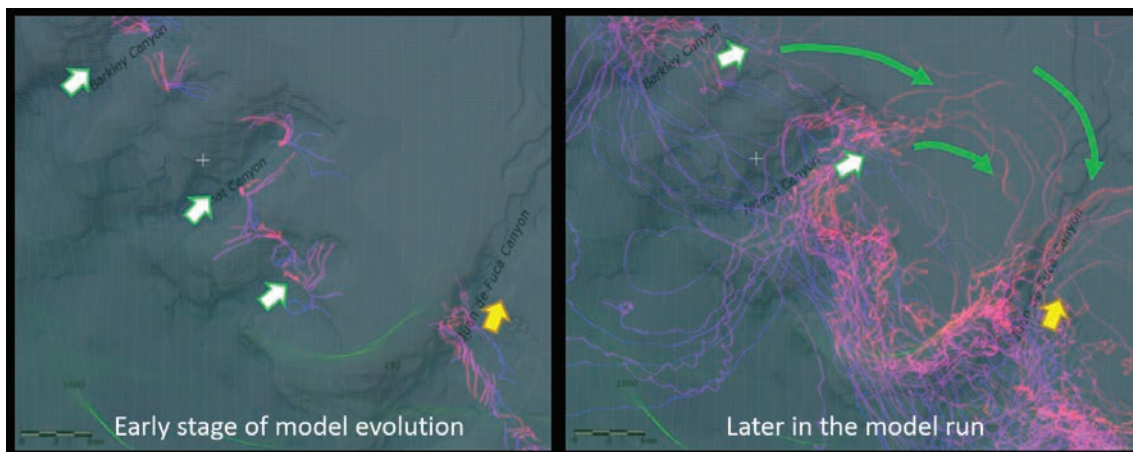


Figure 14.7. Experiment B, excerpted from the Worldwide Telescope visualization engine. Tracers show that in addition to Juan de Fuca Canyon, the Regional Ocean Modeling System model predicts that two of three smaller canyons to the north contribute upwelling water along the indicated (green) pathways.

One could proceed from what amounts to initial suggestions from this simple visualization to explore a more extended series of model runs, and from there to derive an expected flux along various paths. This expectation result might, in turn, motivate a dye trace experiment or other in situ observations to validate the model results.

Experiment C: Dissolved Organic Matter Analysis Using Fourier Transform Ion Cyclotron Resonance Mass Spectrometry

Finally, in experiment C, I consider DOM measurements using FTMS. This method of analyzing complex carbon-based molecules dissolved in water—with typical masses from 100 to 800 daltons (Da)—produces a sequence of extremely narrow peaks that correspond to ionized molecules. Each peak can be assigned a probable mass and, in many cases, a molecular formula. Molecular formula assignment is a Diophantine problem that operates on a small set of candidate atoms: notably, carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur (Sleighter and Hatcher 2007). Formula assignment does not resolve molecular structure, so a single FTMS peak from a naturally occurring water sample is assumed to correspond to the presence of multiple isomers with the same formula. Peak amplitudes in an FTMS spectrum are retained for intersample comparison without any presumption that they correlate with relative concentrations of a specific compound. A question naturally arises: Can new visualization strategies suggest relationships that are not apparent in existing views and analysis of FTMS peaks?

Operating only on the subset of peaks within an FTMS spectrum that are assigned molecular formulas, I refine the question: What do molecular mass and mean peak heights suggest about relationships between different resolved molecular formulas? With no presumption about the large number of *possible* isomers present, a number that can exceed one million for a single molecular formula (Hertkorn et al. 2007; Hertkorn et al. 2008; Ruddigkeit et al. 2012), the general task of resolving molecular compounds in a DOM assembly remains open. Turning to visualization, a commonly used 2D graphing method places a marker for each FTMS molecular formula on a scatter chart with axes for hydrogen-carbon and oxygen-carbon ratios, also known as a *Van Krevelen diagram* (figure 14.8). In WWT, the Van Krevelen scatter chart can be constructed as a distribution

of markers with the addition of a z-axis (for example, showing molecular mass or peak intensity as height for each molecular formula marker as shown in figures 14.9 and 14.10, respectively). Furthermore, the markers can be color-coded depending on atomic constituents (for example, yellow if sulfur is present, green for phosphorus, and so forth). The result is a cloud of several thousand colored dots that are arrayed in three dimensions, which can be viewed from any perspective and flattened to $z = 0$ to produce the traditional Van Krevelen diagram view.

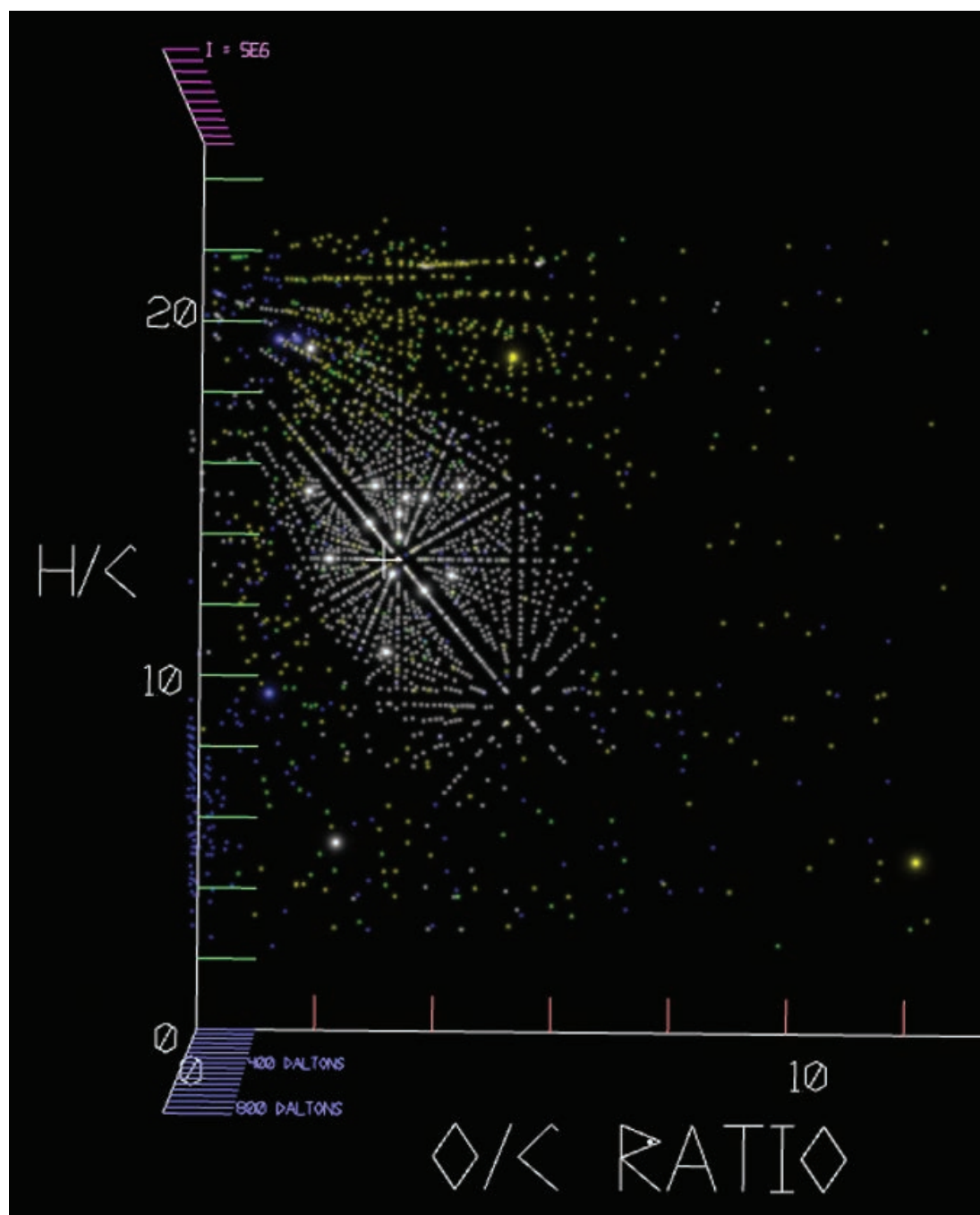


Figure 14.8. Experiment C, excerpted from the Worldwide Telescope visualization engine. Flat representation of a Van Krevelen diagram. Each dot is a molecular formula graphed according to its ratios, oxygen to carbon and hydrogen to carbon. *Yellow* indicates that the formula contains sulfur; *green*, phosphorus; and *blue*, nitrogen.

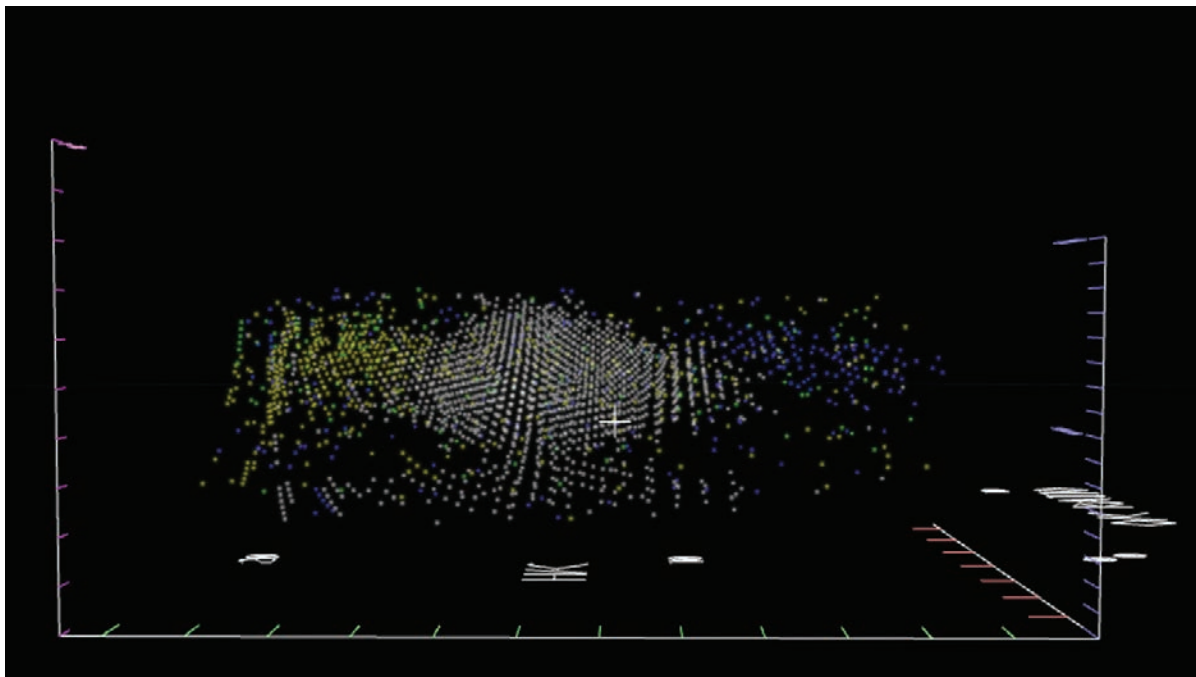


Figure 14.9. Experiment C, excerpted from the Worldwide Telescope visualization engine. A second Van Krevelen diagram view with the z-axis scaled to molecular formula mass. Note the five aligned green molecules at *upper left*, part of a group of six related in formula by differences of CH_2 . Prevalence of sulfur-bearing compounds (*yellow*) can be seen biased to large hydrogen-carbon ratios.

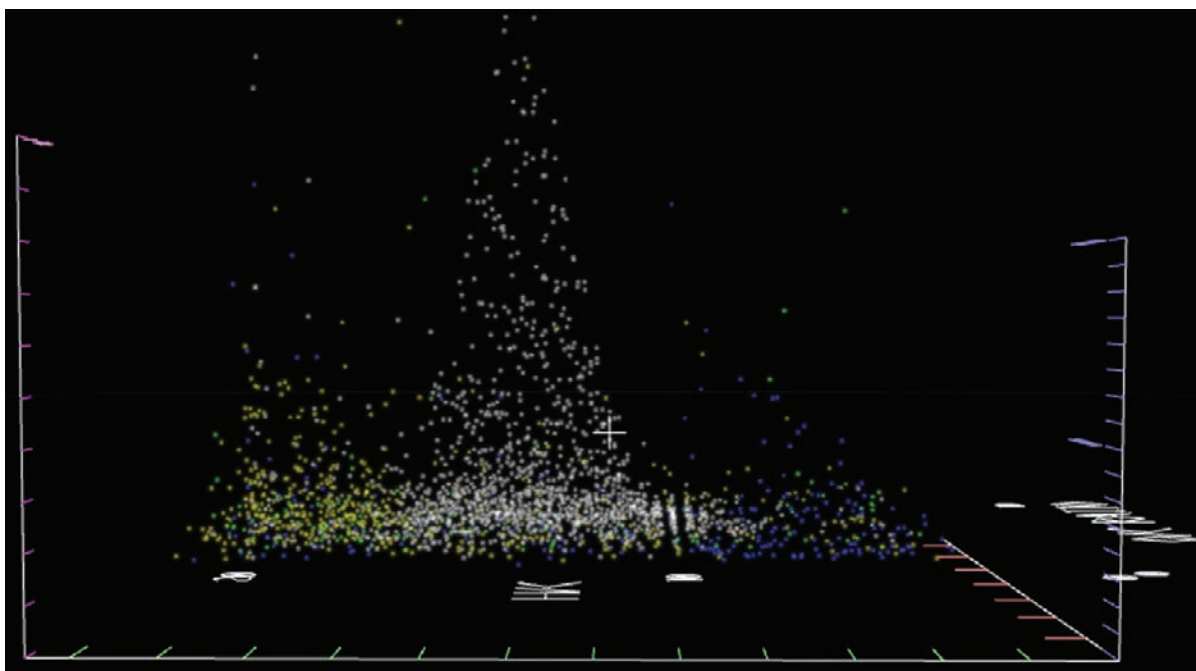


Figure 14.10. Experiment C, excerpted from the Worldwide Telescope visualization engine. A third Van Krevelen diagram view with the z-axis scaled to Fourier Transform Ion Cyclotron Resonance Mass Spectrometry peak intensity.

Consider a smooth sequence of transitions (views) of the data, from traditional/flat ($z = 0$) to mass oriented (z -coordinate scaled by molecular mass) to FTMS peak intensity oriented (z -coordinate scaled to mean FTMS peak intensity) to finally, for the sake of looping, a transition back to the flat view ($z = 0$). The sequence is accomplished by creating keyframes, a sequence of four corresponding view structures with associated sequential time tags. Transition frames are added by interpolating z -axis coordinates and time. That is, a particular marker (molecular formula) will have a z -coordinate in flat, mass-oriented, and peak-oriented views, and interpolated frames will transition each marker between its respective z -coordinates in short time steps. The time slider in WWT then becomes a view control, used by a researcher to move between views while showing the transitions of each individual molecular formula from one view to the next. At this configuration of FTMS peaks in WWT, a further difficulty ensues. The inspection of the marker cloud works well when the researcher can shift the viewing perspective, but it is cumbersome to change perspective while also manipulating the time slider. Therefore, the Auto Loop control is toggled on, and the time elapse rate is increased until the full visualization cycle repeats in, perhaps, 10 seconds. Upon reaching the end point, the view returns to the start (as time is looping), which looks the same as the end point; so the researcher is presented with a smoothly and continuously cycling sequence of three views of the data, and can therefore pan, zoom, yaw, and pitch the viewing perspective at will to focus on regions and molecular formulas of interest. This viewing strategy uses Cartesian coordinates in a sandbox reference frame.

In this visualization, a sequence of six similar phosphorus-containing molecules separated by 14 Da intervals (CH_2 methylene groups) “fly apart” in an unexpected manner during the transition from mass to peak intensity representation (figure 14.11). Hence, this visualization suggests a pattern that can be investigated further using analysis code.

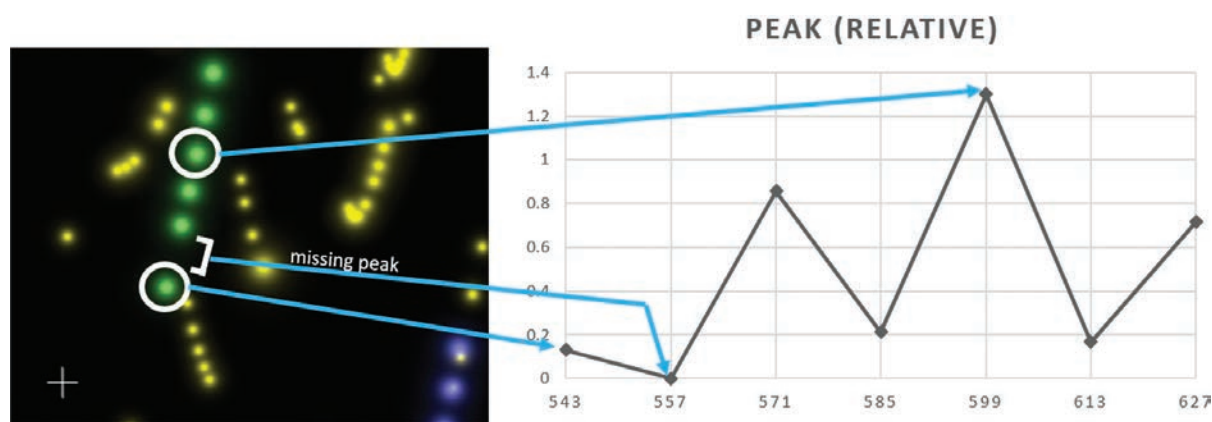


Figure 14.11. Experiment C, excerpted from the Worldwide Telescope visualization engine. *Left:* A Van Krevelen space detail. Six molecular formulas related by mass differences in increments of CH_2 , with one missing. *Right:* Peak graph shows relative Fourier Transform Ion Cyclotron Resonance Mass Spectrometry peak intensity with increasing molecular mass. The sawtooth shape suggests that, in this source water sample collection, there is a variability that overrides a simple correlation between peak intensity and monotonic isomer count.

Conclusion

This chapter touches on a small set of data visualization examples from oceanography. It places visualization alongside analysis and data management as interrelated processes that connect research problems to data. There are premium incentives to shift data access methods—that is, to specifically build data services with a corresponding move toward resource confederation that can lower the barrier to data access, and consequently help meet a growing imperative for data reuse. Toward the goal of visualization, the methods and examples provided here, based on the WWT visualization engine, support the contention that the oceanographic research data challenge—how to effectively analyze and understand new harvests of large complex datasets—is amenable to a technical solution. That is, increasingly complex datasets can be explored via advanced visualization software such as WWT. Although WWT has the capacity for large datasets that exist in a four-dimensional space, its primary strengths are its program-accessible interface and its generic approach to manipulating data (Microsoft Research 2014a, 2014b). WWT and heterogeneous data resources in oceanography will become increasingly amenable to a complementary-tools approach that includes GIS, which will extend 3D visualization and manipulation to the realm of analysis in virtualized environments such as Citrix XenApp and XenDesktop, Microsoft Hyper-V VDI, and VMWare Horizon View (Meza 2014).

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CHAPTER 15

Managing the Visual Landscape of Oregon's Territorial Sea

Paul Manson and Andy Lanier

Abstract

New and emerging proposals for ocean renewable-energy development have raised questions about how to responsibly and sustainably develop these resources. These uses have motivated states and nations to undertake coastal and marine spatial planning. Planning efforts often require collecting new data on various human uses of the ocean. This chapter describes the development and application of a participatory GIS method for assessing visual resources. This method is based on participatory planning and democratic theory, arguing that engaging the politics and values of environmental controversies must be done in “hybrid forums” that enable participatory codevelopment of assessment methods. This unique codevelopment approach allows the capture of new ideas, concerns, and values in the final assessment method, and ultimately allows for more durable agreements. The method uses a group-based field assessment to score views based on local knowledge, elements of visual quality, and computer modeling. This chapter details the development of this method using a stakeholder committee, application of the method in the Oregon Territorial Sea Plan process, and the GIS analysis steps that support this method.

Introduction

Coastal and marine spatial planning (CMSP) efforts have emerged as a key policy priority for coastal nations and regions. This initiative is tied to an international focus on balancing biodiversity and resource conservation with community resilience and economic development. Common to many CMSP efforts is a dedication to participatory processes for planning (Ehler and Douvere 2009). These processes often take the form of participatory deliberation on the coproduction of data for decision-making. This chapter details the development and application of a data coproduction system to collect spatial data on the importance of visual resources in a CMSP context. Called the Community-based Marine Assessment of Aesthetic Resources (C-MAAR), this method is a

community-driven model for visual resource assessment that includes a field survey component tied to GIS modeling to assess visual resources. C-MAAR is unique in its combination of a coastal and marine application, community deliberation tools, and ease of application to rapidly develop policy settings. C-MAAR was developed as part of the Oregon Territorial Sea Plan (TSP) update process. The development history is presented here as it informs ways to transfer this method to other settings.

A critique of quantification systems for values such as visual resources is that they overessentialize a human experience into abstract numbers (Hacking 2000). Further, these numbers are highly dependent on the social settings and various meanings of public decisions. They are not simple market-based values that can be aggregated (Sagoff 2011). Key to these critiques is that the control of the quantification is concentrated among a group of experts or interests that prevent broadening the input and that the standard of proof is different for public debates on how society should use natural systems. The C-MAAR experience in Oregon is the response from the planning agency, the Oregon Department of Land Conservation and Development (DLCD), to avoid some of these pitfalls by increasing participation and bringing community values into the spatial framework for decision-making. These values are critical in resource management because they provide the basis for understanding how differing communities define and conceptualize successful management or sustainability (Norton 2005; Gross 2010) and how policy agreements can form (Sabatier and Jenkins-Smith 1999). The approach detailed in this chapter is an effort to engage visual resource assessment with an acknowledgement that assessments are laden with politics. These politics reach back to the original questions of how and where to locate new ocean renewable-energy developments. Although assessment processes often try to separate the science from the politics, this approach creates a space for deliberations over visual resources that allow for the experts, community representatives, and the public to meet in a “hybrid forum” (Callon et al. 2009). These forums are defined by a mixing of types of knowledge, from laymen to experts and across many issues. These forums allow for controversies to reveal what is important, the possible future that might be planned, and how to build agreement.

This chapter introduces the Oregon TSP update, its policy history, and the context for the visual inventory. It also discusses the challenges involved with obtaining, and options for soliciting, visual resource values from communities. The tension between expert-driven methods and experiential methods for assessing visual values is discussed. Next, the chapter explores development of the method, including the participatory process used. Oregon’s ocean-planning experience is defined by a dedication to distributed data development and engaged participation by community and user groups. This dedication to public involvement is captured in Oregon’s statewide planning goals (codified in state law), and it influenced the design of C-MAAR and its participatory components. This chapter discusses how the C-MAAR method was codeveloped with community members in joint method development workshops in a live policy-process setting. The C-MAAR approach, with its thorough stakeholder committee involvement, appears to offer a way to successfully bridge these two interests: scientific rigor and responsiveness to public and policy needs. Finally, the chapter presents the technical details of C-MAAR, how it was applied, and discusses the outputs included in the planning process. The discussion and conclusion explore the challenges and strengths of the C-MAAR method and how to resolve key tensions in participatory GIS applications.

Background

The Oregon coast is an internationally recognized tourist destination. Over 20 million visits are made to Oregon’s coastal parks each year (OPRD 2005). Scenic enjoyment is the third-most commonly stated primary recreational activity that visitors say they engage in on Oregon’s coastal beaches

(Shelby and Tokarczyk 2002). In addition, the Oregon coast highway (Pacific Coast Scenic Byway) has been federally recognized by the National Scenic Byways program, established by Congress and administered by the US Department of Transportation Federal Highway Administration. In addition to being one of the first scenic byways in the country, it has also been designated as an “All American Road,” which recognizes US 101 as possessing “multiple intrinsic qualities that are nationally significant and [having] one-of-a-kind features that do not exist elsewhere” (CH2MHill 1997). Oregon’s coastline is also unique in that it has over 70 state parks that run along the highway, providing “public access and resource protection in a way that is unrivaled by any other US coastline park system” (CH2MHill 1997).

TSP Context

Ocean renewable-energy developers came to Oregon in 2007 seeking to deploy wave energy devices. These developers were taking advantage of both a series of policy goals to expand renewable energy by the states of the West Coast, as well as make use of the massive energy potential of the Pacific Ocean off Oregon. This interest resulted in a series of claims on the ocean for developers to use certain areas but outside an organized planning approach. The initial lack of a coordinated framework to assess the impacts of these claims led to a multiyear ocean planning effort by the State of Oregon through its statewide planning agency, DLCD. DLCD was charged with understanding the current human uses and natural resources that might need protection or consideration before siting of energy devices. DLCD’s planning jurisdiction is the territorial sea, a 3 nm ribbon of ocean along the coast. The new planning policy was developed through an update to the state’s TSP. This plan identifies the state priorities for management of the territorial sea and guides partner agencies in implementing state policy for the ocean.

The TSP update provided the process to consider new energy uses in a comprehensive framework. This process was required to assess resources and uses that might be in conflict and consider how best to locate new renewable-energy projects to minimize negative impacts. At the beginning, data for the planning process was not readily available, and coverage often did not include the full extent of the territorial sea. DLCD’s first planning task was to develop new spatial data products with partners, ocean users, and community groups. A hallmark of the Oregon planning law is extensive public involvement. The TSP experience expanded this concept through participatory data development. These data products include public participation GIS (PPGIS) datasets, building on previous regional efforts to develop stakeholder and community-driven data (Bonzon et al. 2005). The commercial and sport fishing data collection was based on a participatory model of sitting down with boat captains to map out areas of important fishing effort (Steinback et al. 2010). Likewise, an effort to map the nonconsumptive recreation ocean-user community was also based on a PPGIS model (LaFranchi and Daugherty 2011). In addition to the PPGIS projects, the planning process was guided by a series of citizen-involvement committees that reviewed and contributed to the research and data collection. These elements formed the basis of the C-MAAR process during planning. Assembling these data products allowed for analyses of interactions among different user groups and evaluation of potential conflicts with new energy developments. As the planning process moved forward, it became clear that local community residents were concerned that future energy development on the ocean would potentially impact the quality of their views. Public testimony and feedback during meetings underscored the importance of considering aesthetic (e.g., viewshed) impacts for marine renewable-energy siting. In response to this concern, which supported concerns previously presented by the Oregon Parks and Recreation Department (OPRD), the decision was made to develop and implement a visual resource inventory for the Oregon coast.

This decision was supported by language in Oregon's Statewide Planning Goal 19, which is reiterated in TSP, that states agencies, through programs, approvals, and other actions, shall "protect and encourage the beneficial uses of ocean resources such as ... aesthetic enjoyment." Additionally, Oregon's Ocean Shore Management Plan, a Federal Energy Regulatory Commission–approved "comprehensive plan," notes that OPRD (2005) "may identify important 'scenic features' that should be protected from development or other impacts for their scenic value." To support the development of a visual resource inventory, an advisory committee of local community representatives, user group representatives, and management agencies was convened to ensure community involvement. Through this committee, the C-MAAR methodology was developed.

A final feature of the Oregon TSP update is that the process had to manage unknown future ocean energy technologies. Whereas ideas existed about the potential size and shape of some technologies, most of them were unproven; and uncertainties existed about the likelihood of actual industrial-scale development. Other visual-resource efforts in the waters off the United Kingdom and Europe, as well as on the US East Coast, were based on modeling the possible visual impacts of known technologies. For example, offshore wind development uses mature turbine and pylon designs that can be modeled. At the time, wind was not being considered within Oregon's territorial sea because of the steep seafloor and depths. Similarly, there were no clear high-priority areas for energy developers, granted the wide range of possible technologies being considered at the time. Instead, the Oregon TSP process inventoried and assessed coastal visual resources to identify possible areas in which conflicts would be low. This type of assessment reflects an ongoing tension in marine spatial planning and ocean renewable energy: a project-based approach versus a programmatic zoning approach. Project approaches can be more certain in their assessments but also require that assumptions be made on technology and placement. This approach can also be riskier for developers, who identify their priorities first and then have to defend that option. The programmatic approach, on the other hand, allows for a comprehensive examination but with less specificity on the actual impacts.

Visual Resource Assessment Techniques and Theory

Visual resource assessments have a long tradition in various intellectual disciplines, each with different assumptions about the value systems and rationale for including visual values (Dakin 2003). From an economic or utilitarian standpoint, visual resources are part of a package of benefits that include other economic values such as recreation or housing. Another perspective is to understand visual resources as part of a sense of place. In the sense of place framework, visual resources are part of defining identity, values, and community. These two perspectives can occupy opposing positions, the first focused more on individual and market-type values while the second is focused on communal and shared values. In between are other variations on values, such as behavioral or environmental psychological theory. The economic model is more commonly found in policy settings as it matches the logic of efficiency and effectiveness that dominates cost-benefit rationale in these decision-making settings (Frank 2000).

This tension has methodological implications. Economic or utilitarian models focus on tools to discover hidden values from individuals and reveal these values for analysis. Examples of this type of assessment include developing policy priorities that are driven by housing values versus community values. This perspective assumes the individual as the unit of analysis and that social value can be assessed, in aggregate, through tools to replicate the values that would be found in market exchanges (Stone 2001). This process leads to an expert-driven assessment method for

modeling value. Increasingly, the economic or utilitarian models for visual resources are expanding to include more complex understandings of value. From the economic model, natural systems provide aesthetic and visual amenities for human communities through sights, sounds, smells, and touch (Millennium Ecosystem Assessment 2003; De Groot et al. 2010). Visual resources are found in a wide diversity of settings that are not necessarily “natural” or “pristine” settings, but can be anthropogenic green spaces in urban areas; restoration sites; or managed landscapes such as forestry, agriculture, or open space and protected areas. These benefits can stand alone as a service or contribute to other benefits such as recreation, a sense of place, or cultural heritage. Visual resources, also seen as amenities, provide important contributions to market values, such as real estate values for homes or vacation properties (Lutzenhiser and Netusil 2001).

The communitarian perspective is more focused on interactions among community members. Here, the visual resources are not consumed as commodities, but likely are constitutive values that define a place and its people (Tuan 1977). In this assessment type, the methods tend to be experiential, in which participants are asked to share their experiences with the goal of understanding the meaning behind views (as opposed to the utilitarian value). This expert-experiential tension has an impact on how the tools for visual resources are developed. Sense of place has been proposed as a critical tool for understanding the values and meanings that communities hold in natural resource decisions. Sense of place is particularly powerful as it connects physical space, human values, and individual identities with rich layers of meaning (Relph 1976; Tuan 1977; Williams and Stewart 1998). This perspective commonly suggests personal intimate relationships between “self” and “place.” Thus, a “sense of place” is often understood largely in terms of positive affective qualities of place-attachment. Traditional and familial knowledge are often strongly linked to places. Stories and events are tied through locations, and locations can become symbols for the values that flow through a family history (Basso 1996). Place has also come to stand as a measure of civic community or community attachment (Kemmis 1992; Clark and Stein 2003). This attachment is a primary concern of any visual or aesthetic assessment that is included in local deliberations on the use of land or sea space.

Visual resource management has experienced a more expert-driven focus over time, in part because the biophysical nature of views is more readily amenable to spatial modeling. Visual assessments can use expert opinion, based on objective categories and measures, or they can rely on individual perceptions and experiences (Dakin 2003). Critiques of expert-driven methods suggest a need to capture the experiential perspectives of the viewers (Daniel 2001). Expert-based models try to fit the environment into categories and scales that simplify the environment. In general, GIS has a tendency toward this expert model versus the experiential model (Duncan 2006; Lejano 2008). The challenge for expert-based models is that the simplification of views or sense of place can overessentialize elements in the biophysical world because of data availability, the choice of categories, the ease of analysis and visualization, or in response to immediate political concerns. Thus, experiential and participatory systems can help overcome simplifications and generalizations that might mis- or underrepresent local preferences and goals (Duncan 2006). Far less attention has been paid to the local community and residents, so working in participatory contexts can open new possibilities for reconfiguring the conventional understandings of information that traditional GIS can produce (Elwood 2006).

At the same time, sense of place has been noted as being richly theorized, but not fully developed empirically (Stedman 2003). Efforts to add empirical tools have allowed for quantitative investigations of place (Shamai 1991). However, limits have been identified in the progress of these examinations, especially in converting qualitative accounts of place to quantitative indexes. A chief concern is that sense of place can overestimate a common versus contested meaning, and

that the scale of sense of place is often not investigated (Cheng and Daniels 2003). This recognition suggests that current efforts to understand the sense of place must work to better understand the levels of agreement within communities over sense of place, the contingency of this meaning on larger relationships in a region, and the role of scale in its individual perception. This need for understanding is particularly true of coastal and ocean settings, in which local community preferences can be complex. In the case of Oregon, debate occurred about the types and levels of appropriate industrial uses of the ocean and their potential impacts on views. For example, commercial fishing fleets introduce cultural modifications on otherwise “natural” views, including bright floodlights and the presence of vessels. However, this view has become iconic, representing economic resilience for some community members but not all. This value is tested when new ocean-based users, such as ocean renewable energy, emerge.

This review of some key issues in visual and aesthetic theory and practice helps describe a unique challenge for the application of visual resource assessments—namely, the tension between utilitarian-based and experience-based models. Utilitarian-based models suggest that comparisons can be made across different value sets based on the level of use. Experiences are not as easy to compare. Efforts to distill metrics such as visitor counts or visitor days show how the value of the experience is lost through simple use metrics. However, experiences also more accurately capture what many feel about a place, more than a measurement of use can. Each metric applies to a logic in public policy that can be difficult to resolve.

Once the basis of the valuation is identified, another methodological challenge returns. The expert versus participatory models provide a similar common challenge in planning processes. The experts have access to unique tools and knowledge and are expected to act for the common good; however, for such experiential values as views, this expertise is easy to challenge because it evades the usual conceptions of rationality and standardization (Daniel 2001). Although the C-MAAR approach proposed here does not solve these challenges, it attempts to respond to these concerns and balance the experts and participants, and also endeavors to meet the time and resource constraints that exist in planning processes. By engaging in local participation to evaluate views, the experiential component of place can be captured and described in more definition using the constituent parts of the viewer experience.

Methods

Federal land management agencies use several accepted methodologies to manage scenic resources (BLM 1980a, 1980b; Smardon et al. 1988; US Department of Agriculture Forest Service 1995; Gobster 1996). These methods, which involve conducting inventories of scenic resources and evaluating potential changes based on established criteria and objectives, reflect the expert and use-based model of assessing views. The degree to which a renewable-energy facility (or other development) in Oregon’s territorial sea has an impact on aesthetic resources depends on a variety of factors, some of which are comparable to land-based scenic-impact assessments. Modeling and adapting these visual subordination standards for projects proposed in the territorial sea will allow the state to “provide time-tested qualitative benchmarks that can be measured using objective methods” (Apostol 2009). The existing models rely on identifying the key physical attributes of a place and its views. These attributes are scored based on how they are affected or interact with other human or naturalized features. The scoring is then combined across groupings of the attributes to provide composite scores. Additionally, the perspective of the view and its distance from the

viewer are incorporated to ultimately derive a value for the view. These methods were developed for terrestrial applications, with a focus on western US landscapes.

Several factors were incorporated to adapt the federal landscape model to state waters for use in the Oregon TSP update. One issue was assessing the different attributes and features of a coastal and marine view that are not typically the focus of federal visual assessment processes. The other main factor was the desire to incorporate public involvement in the assessments. The methodology settled on using a participatory field team, followed by expert-driven spatial analysis and scrutiny of the results in a public setting during multiple public meetings. The following section explores each of these factors and how the tool was developed and deployed on the Oregon coast.

Adoption and Adaptation of Established Methods

The C-MAAR application for the TSP update uses two discrete processes, the planning phase and the project phase. During the planning phase, work is done to collect baseline visual resource information and adopt the standards that will be applied in any review of a project during the project phase. These processes are described in the following sections. The project phase involves applying the planning tool to assess proposals for renewable-energy development. The project phase tiers from the planning level analysis but may also include focused reapplication of the tool to respond to particular proposal details. In 2013, the planning process for the Oregon TSP ended, leading to the project phase.

The TSP update process relies on a heavily involved advisory committee of local citizens, regional interests, and agency representatives. The committee provided support in the development of the C-MAAR methodology. The design of the field protocol, inventory of the sites, and application of the method were all developed with and reviewed by the committee. This approach allowed for the joining of the expert and experiential components of visual resources. Expert representatives provided insight on the technical options and the latest research methods. The experiential perspective of the committee contributed the substantive concerns and values on viewsheds. This contribution was essential for identifying the new coastal and marine viewshed features and attributes to be included in the final field datasheet.

Planning the Inventory

The C-MAAR tool starts with creating an initial inventory of viewpoints in the study area. For Oregon, the inventory included almost 150 viewpoints on public land. The choice to include only public viewpoints was an important one. The citizens and agencies involved made an early decision that views included in the plan must be of a public nature: they must be views from places that all Oregonians and coastal visitors can use and are likely to visit. This choice also assured that access to conduct field surveys would be easy and that others could evaluate the views for themselves as part of the public process. An initial inventory of viewpoints was developed from an inventory from OPRD. This inventory included approximately 100 potential viewpoints. In addition to the OPRD inventory, an additional 50 potential sites were identified from a review of county and city planning documents, as well as through outreach to local staff and elected officials. These other sites were located in county parks, on federal lands, and on public right-of-way or beach access points.

Conducting the Assessments

C-MAAR employs a field survey instrument to evaluate publicly accessible viewpoints and collect data on their visual quality. The survey evaluates seven key features using a numeric scale of 0 to 5, with one exception. The features are as follows:

- Landform: the steepness of vertical relief and diversity of landform features such as rocks, cliffs, and headlands.
- Vegetation: the mix and diversity of species and communities of vegetation and how they contribute to the scene (e.g., interesting forms, patterns, and so forth).
- Water: additional water features aside from the ocean, meant to capture rivers, lakes, waterfalls, coves, tide pools, unique wave breaks, waves breaking on offshore rocks, and so forth.
- Color: the diversity of colors in multiple natural media, including sand, soil, water, and rock.
- Adjacent Scenery: the surroundings that contribute to the view being evaluated. This feature is terrestrially focused and tends to evaluate the natural or urban setting.
- Scarcity: a relative judgment of how common or scarce the view is, as it relates to other views along Oregon's coastline.
- Cultural Modifications: the beneficial and detrimental human activities and developments within the view. The scoring of these features is the only category that allows for a negative score, in cases of anthropogenic impacts to the view.

In the field, the survey team reviews these categories one at a time and then scores them. The teams may be composed of state planning staff, local planning staff, and elected officials. In the case of Oregon, the recruitment of teams from these groups was intended to balance a need for public participation and assessing views that are representative of the larger community. Teams could have been developed using local residents or visitors, but the sampling or recruitment strategy would have been problematic. This case is especially true in communities that have high rates of absentee owners, such as communities that have many summer homes. With the use of elected officials and senior planning staff, representation and accountability were built into the review teams. Planners, as staff in these small communities, were accountable to elected officials, which was demonstrated when elected officials checked in on planners through the review process. Team size also varied; in some communities that showed greater interest in participating, teams grew to eight people. In areas with lower levels of interest and availability, the team size was at least three evaluators.

The first task for the team was to select the place from which to assess the view and to delineate the extent of the view. Clues for identifying the point for assessing the view include developed elements, such as interpretive signs or constructed viewpoint platforms. Observing where visitors tend to stand is another option. Standing on the sand below the vegetation line on beaches is recommended for capturing the full view, although in some cases the tops of dunes or berms may be appropriate. Once the point is selected, the team discusses how far to the left and the right to include in the view. Usually, the view is limited to the top of the beach where the terrestrial vegetation begins, but sometimes it is further inland if unique features attract the eye. This view creates an arc from the top of the sandy portion of the beach on one side of the viewer to the end of the sandy portion on the other side. Only features that are inside this view arc are considered in the scoring, with the exception of the features captured in the evaluation category of "Adjacent Scenery," which includes the view inland from the viewpoint, or the setting in which the viewpoint exists.

The features are discussed and documented in a narrative that is developed with the review team. A group facilitator or recorder notes the descriptions, features, place-names, and comments from the review team. This record keeping provides important documentation for any future questions or reviews. The team then openly discusses how to score each category. The team works toward a consensus on the values. In the case of Oregon, reaching consensus was almost always successful.

When agreement cannot be reached, two assessments can be recorded and passed on for review in the decision-making process. The values of each site are totaled to produce a composite scenic quality value across all seven attributes. These values are then used to discuss how well the method captures the view based on local ideas about the aesthetics of the site. In the application for Oregon, the 150 sites on the coast generated scores that ranged from 7 to 30.5. High-scoring sites tended to be higher-elevation locations, in naturalized settings, with steep relief, often on headlands or capes. Because water features were a separate element in the scoring, sites without freshwater streams, waterfalls, or other interesting water features (such as waves crashing on close-to-shore rocks or tide pools) often scored slightly lower, even if the view seemed otherwise iconic. Presence of seasonal or temporal features such as tide pools may vary over the year, so evaluators' previous experience with, and local knowledge of, the sites was important so that those features were incorporated in the assessment. The field protocol requires that similar seasonal and weather conditions be present throughout the study period. For the application in Oregon, the summer months were used and assessments occurred on sunny days with good visibility. Wind, sea state, and weather conditions are recorded in the assessment documentation in case these conditions were required to be reviewed later. Time of day was also noted, and reviewers were asked to consider that factor as well.

During the fieldwork, participants easily agreed on most of the scores and how to describe and classify what they saw. The primary area of contention concerned features that fall within the Cultural Modifications category. These features include all anthropogenic items in the view, such as historic lighthouses, jetties, signage, riprap, and significant automobile use on the beach. The last item drew contention as some participants in the surveys objected strongly to large numbers of vehicles on the beach, whereas in some cases it is tied to traditional beach uses such as surfing and boat launching for a historic dory fleet. Previous experience with the sites and local knowledge was important because vehicular use varies over time, and only sites that are known to consistently have large numbers of vehicles, such as boat launch areas, typically had points docked for this particular cultural modification.

With all the attributes collected, the results were then summed to assess the view. The assessment used the scenic quality rating scoring categories used in the Bureau of Land Management (BLM) methodology. Views that scored 19 or greater were given an A rating; 12–18, a B rating; and below 12, a C rating. This scoring allows for a comparison in the field, often in terms of how the view compares with others surveyed with the same rating. Additionally, the committee asked for an emotional measure to be included in the field survey instrument. This experiential question (as the first question in the survey) asked field surveyors to evaluate how they felt upon seeing the view. The group used a 10-point scale to evaluate the general “feel of the place.” Although this rating was not included in the data analysis (for scoring purposes), it was meant to be a check on the quantitative model and to serve as a balance with previous experience that people may have had at the sites. This emotional scale is also compared to the score rating to see if there is an approximate match. The scoring of the individual attributes represented constituents of the experiential view, and the emotional ranking was a second measure to test the validity of these measures. With the site level data collected, the next requirement was to convert the data to spatial datasets that could interact with the rest of the planning data.

Field data was brought back to the office and processed for analysis. The datasheet includes the quantitative data on scoring for each attribute. It also includes narrative data on the location and attributes. The field teams document the particular features and elements of the view that justify the scoring for each attribute. Additionally, the general site conditions and special observations are noted on the datasheet. For example, the water feature attribute section that is often included notes naming the features in the view and the type of wave break or action present. All the data is entered into a database to allow for reporting. The results of the fieldwork are then processed into a summary report for public

review and comment. Figure 15.1 presents an example of a report on one of the sites. This document includes a panoramic photo of the view, the scoring data, and narratives on the site. This easy-to-review document facilitated the review of the fieldwork and allowed for public involvement, even after site reviews. The document also facilitated easy comparisons of sites, which built support for the findings.


Ecola Point Viewpoint		
SITE NAME Ecola Point Viewpoint	SITE ID: OPRD091	COUNTY Clatsop
DESCRIPTION Accessed via a short trail from Crescent Beach parking lot at Ecola State Park leading out to Ecola Point. A viewing deck provides expansive (iconic) ocean, shoreline, seastack and Tillamook Rock Lighthouse views.		
DATE: 5/7/12	TIME: 15:20	WEATHER: Partly cloudy
		WIND: N/A
Panorama Photos		
		
ATTRIBUTE	SCORE	DESCRIPTION
Landform	5	Coastal headlands to the south (Neahkanie Mountain and Cape Falcon), coast range mountains, numerous large seastacks along the beach (many of which are vegetated), including Haystack Rock, various small to mid-sized offshore rocks (e.g., Sea Lion Rock) at Ecola Point, spires, caves, sandy and cobble beaches, coastal bluffs, steep vertical cliffs, coastal lowlands, sand spit (Ecola Cr.). The expansive ocean view to the north includes Tillamook Rock offshore, various stages of landslides, Indian Beach, Tillamook Head, coastal bluffs with a mix of sandstone and basaltic materials.
Vegetation	5	Coastal scrub shrub in the foreground with salal, wild cucumber, native roses, and elderberry along coastal bluff grasslands and sitka spruce forest, distant forests prevalent on headlands. Bull kelp and other intertidal and subtidal seaweeds visible at Ecola Point. Trees clinging to rocks add visual variety in the foreground.
Water	5	Waves crashing on offshore rocks, especially at Ecola Point in the foreground, coves in both directions (Crescent and Indian Beach), mouth of two creeks.
Color	5	Blue ocean with lots of variety due to reef and rocky shore/kelp beds punctuated by dark colored offshore rocks and white surf. Bright green of coastal shrubs and grasslands, dark green forests all contrast with tan sandy beach. Rust colored bluffs (some from landslides) provide interest, pink flowers in vetch and rose provide seasonal interest.
Adjacent	3	Park setting including trail, lookout, boardwalk, sitka spruce forest, grassy bluffs, day use parking lot.
Scarcity	5	Iconic views to the north and south, including Haystack Rock and Nehakanie Mountain/Cape Falcon, Ecola Point, Tillamook Head and Tillamook Rock/Lighthouse.
Cultural	1	Cannon Beach tucked into shoreline in distance, parking lot at Indian Beach, signs and rusting fence in immediate foreground (below the edge of the view), all provide for small detractors from the view. However, Tillamook Head Lighthouse in the distance provides interest due to its uniqueness.
Total	29	

Figure 15.1. Example of a data report from a field survey. Photo by Laurel Hillmann, Oregon Parks and Recreation Department.

The quantitative data provides values for the points, and the policy guidance requires that this information be transformed into spatially explicit data to inform decisions about particular spaces on the ocean surface. After the fieldwork is conducted, the values from the data collection are then used to produce spatial outputs that can interact with other planning data. The C-MAAR tool used ArcGIS 10 software to develop viewshed maps based on the points surveyed and assign the various scoring rules to the polygons. This analysis includes three basic steps: generate visible areas, then apply distance zones, and finally add the values from the field data.

The viewshed analysis tool uses a model of the earth's terrain to measure the distance that is visible from a point, based on the curvature of the earth, physical obstacles, and light refraction. The elevation model played a large role in determining the areas that might be visible. The topography of the coast and shoreline were modeled using a digital elevation model (DEM) acquired from federal data providers. For much of the Oregon coast, the National Elevation Dataset provides 10 m horizontal resolution models. The viewpoints, as measured with GPS in the field, were captured using a different level of accuracy. Therefore, using a very detailed model could add uncertainty to the model, creating

visual artifacts in viewshed analysis. The points might fall in between the DEM's modeled world, creating artificial shadows or obstacles to views. Using too coarse a model can oversimplify the world, making views overly expansive and inclusive of areas. This discrepancy was managed in the GIS by using a random distribution of “viewers” (computer-generated points) to simulate vantage points.

Viewpoints were buffered by 50 m, and then 40 new points were randomly distributed within this area. This method was developed for C-MAAR, and the specifications were based on the iterative testing of different buffers and numbers of points with the stakeholder committee. The viewsheds calculated by the software created 40 overlapping view areas, shown in the map area by a varying intensity of blue (figure 15.2). The more intense the color, the greater the number of overlapping views. Darker colors in the figure show areas in which more views overlap, and thus areas that have a higher certainty of the actual viewshed being covered.

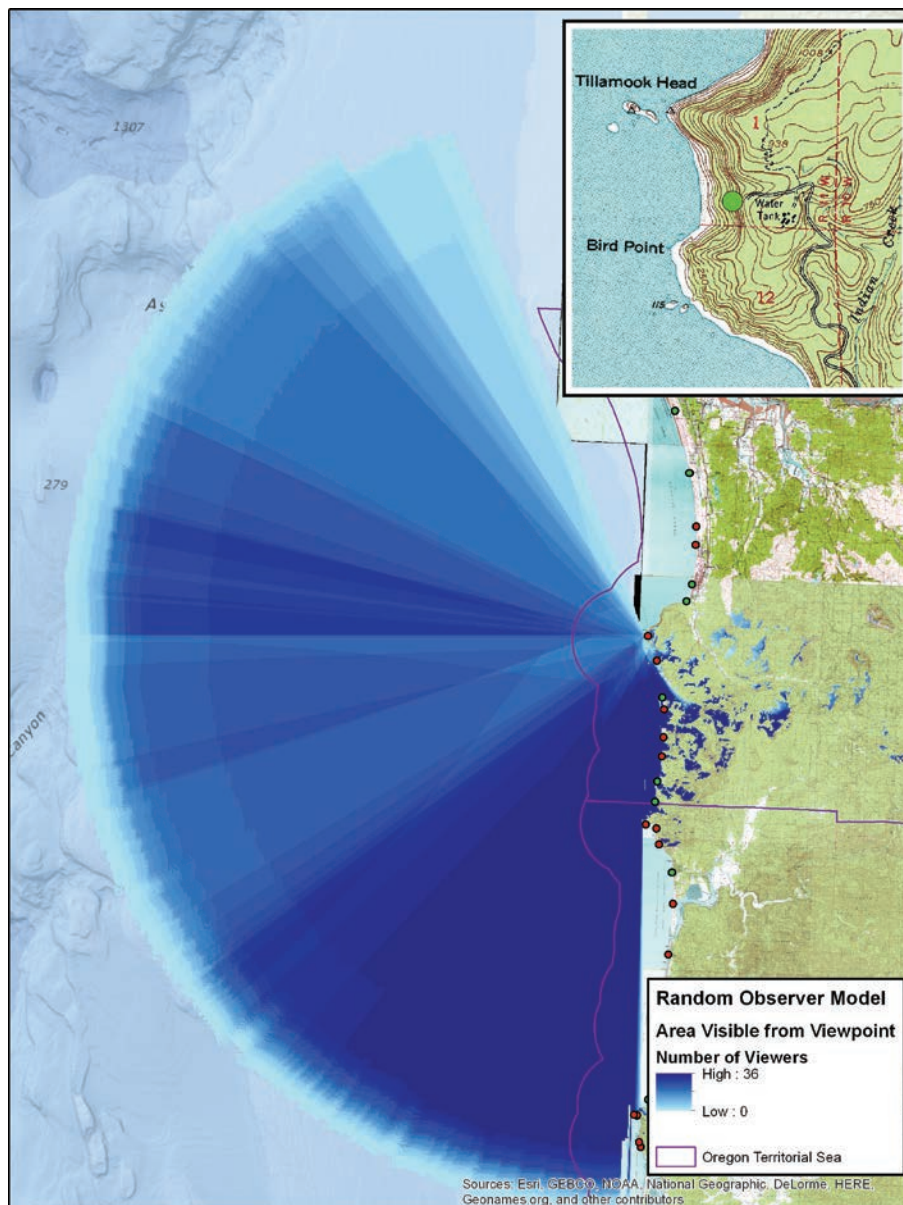


Figure 15.2. Viewshed model application with random viewpoints and density of views measured as seen from Ecola State Park on the northern Oregon coast. The inset map shows the location of the viewpoint within the state park. Data sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors.

For each of the 150 viewpoints, this process was applied, creating more complex and overlapping representations of the possible views on the Oregon coast. These overlapping arcs were then attached to the field-based score and ranked in scenic quality ratings, of *A*, *B*, and *C*, based on the BLM rating system. Multiple views overlap, each with a different score. The scoring was developed so that it links to a design review standard for any future energy proposals. The higher the score, the more visually subordinate the development must be. The highest scores may exclude development, unless it can be shown not to attract attention. In future energy design reviews, proposals will be evaluated from each of the overlapping ratings and viewpoints. The varying levels of quality are also broken down by distance from the viewer to capture the intensity of potential impacts from any development. The BLM method identifies the fore-, middle (mid), and backgrounds and an additional seldom seen area (BLM 1980a, 1980b). These distances were reviewed with the committee and adapted based on stakeholder input on visible objects at various distances. The committee decided that the fore- and midground distances were visually difficult to separate in the ocean context. These two distances were collapsed into one. The scenic quality ratings from the field are combined with these distance ranges to create several classes of views based on their importance and sensitivity.

The field data is compiled in a point feature class that contains the attributes from the surveys. Figure 15.3 shows the location of the inventoried viewpoints, as well as the initial values collected in the field for each view before the viewshed analysis. The model iteratively moves from row to row and runs the model for each viewpoint. Each raster viewshed output is stored and named using the point feature class data. The final output of the model run is a viewshed for each viewpoint and a raster with the viewshed value and distance zone. Processing each of the viewshed areas for the 150 survey points requires processing 40 individual viewshed models for each of the “random” observers placed at each site visited. These 40 random viewshed results can be combined as a weighted measure of density based on the number of overlapping views, or the maximum extent of views can be used. In the Oregon application, the maximum extent was used as a more conservative measure of possible visual impact. This decision was made by the stakeholder committee, representing a policy preference to take a more precautionary approach. Using this new composite viewshed area, the model applies rules for scores based on distance zones. Initial testing with the review committee revealed that the many steps involved required the GIS analyst to be heavily involved in processing the views. To resolve this issue, the ArcGIS ModelBuilder application was used in the development of C-MAAR to automate the processing (see “Supplemental Resources” at the end of this chapter).

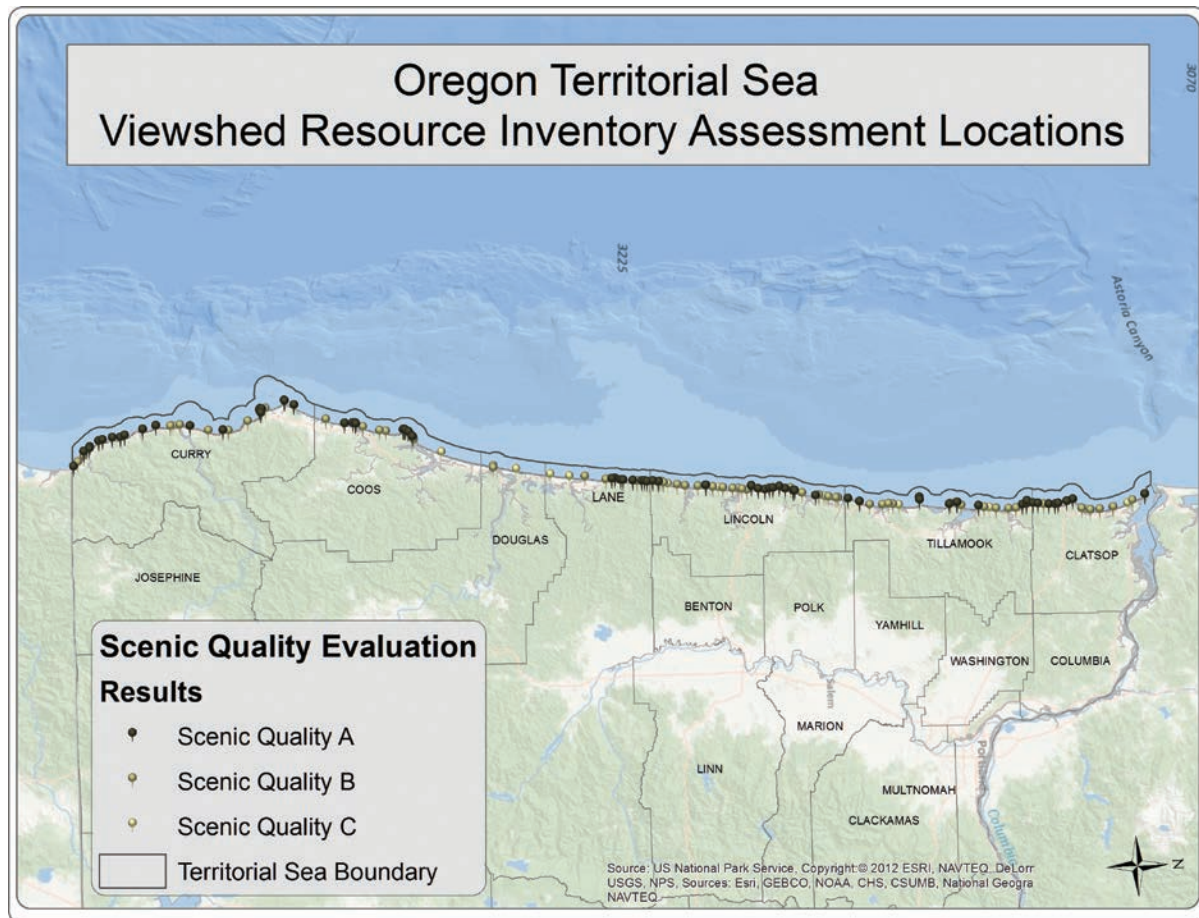


Figure 15.3. Viewpoint inventory and initial scenic quality rating values from field surveys. Source: US National Park Service, Copyright: © 2012 Esri, NAVTEQ, DeLorme, USGS, NPS; data sources: Esri, GEBCO, NOAA, CHS, CSUMB, National Geographic, and NAVTEQ.

Because the method was developed with the advisory committee, the implications of the choices made were tested against potential future scenarios. For example, if future potential development areas looked as if they were going to be too easily visible from high scoring sites, future development could be limited in those places. The committee discussed the implications of the standards and strove to balance development and view conservation priorities. As the viewshed maps were generated and the field data values assigned to them, a final step that the committee handled was assembling multiple maps into a single composite coastwide dataset. This compilation was necessary to ensure the data fit with the other data types, but it required flattening the complexity of the multiple sites into a single representation, which disconnected the coastwide data from the reality it was meant to capture. Some participants in the planning process raised concerns that this representation seemed to restrict development almost entirely. Developing online access to the visual resource data has helped allow for interactive queries of the data, but the representation of the results is almost as important as the results themselves.

Another policy choice made in the development of the tool was the designation of a special class of views that have exceptionally high visual values. These views were predominantly from iconic vantage points. For most views, the methodology developed provided for decreasing visual resource classes as the distance from the viewpoint increases. For these “special areas,” it was determined that the distance from the view should not affect the resource class, which creates a large area of a

high-value visual resource class on the ocean. In part, this came about as the committee recognized that Oregon's territorial sea did not already have the types of management situations described in the BLM policy manual that qualified as special areas. This compromise also resulted from the committee's modification of the BLM Visual Resource Class table. The committee chose a cutoff score rating of 24, and vetted in multiple public meetings, as an appropriate break for sites to fall into this viewpoint category. As discussed in the next section, these areas represent the most protected class of visual resources.

Translating Models to Support Policy

Once the Visual Resource Inventory Assessments were conducted and the spatial data was generated to extend the policy out to sea, the results were translated into proscriptions on uses and impacts. The committee used the C-MAAR tool to craft a series of visual resource classes that connected the scenic quality ratings to the level of development likely to be allowed once proposals and visualizations occurred. This strategy follows a similar logic to the terrestrial visual resource tools developed by BLM, but the feature classes were adapted to recognize that development on the ocean is more likely to attract attention because of the lack of physical variation at sea (and the inability to modify design to minimize impact because of safety-at-sea considerations).

The scores from the field are translated into four visual resource classes: I–IV, as shown in figure 15.4. Class I areas are those with the highest value and are either in the foreground/midground of high scenic quality viewpoints or within the viewshed of a special-area viewpoint. The objective of class I areas is to preserve the existing seascape character; and although development is not precluded, it is not allowed to attract attention. Class II areas are expected to allow limited development as long as the existing character of the view is maintained and the new development attracts only minimal attention. Class III allows for more development, and it may attract the attention of viewers. However, the development may not dominate the view. The final class, class IV, allows development; and it may be the dominant feature, although mitigation is expected to manage the impacts.

Visual Resource Viewshed Class Derivation (I-IV)				
Special Areas		I	I	I
Scenic Quality	A	I	II	II
	B	II	III	III
				IV
	C	III	IV	IV
		Fore/Midground (0 – 5 miles)	Background (5-15 mi)	Seldom Seen (15 mi and beyond)
		Distance zones		

Figure 15.4. Visual resource scenic class structure and scoring.

A final step in the C-MAAR process is to present the results. Cartographically, the outputs can become difficult to represent. There are three values per viewpoint; and thus in the case of Oregon, over 450 unique view and value combinations are possible. The results then must be carefully presented, based on the needs of the audience for the product. Because the highest-value view data is the most important, the data was simplified into the maximum value and converted to polygons for cartographic symbolization. In Oregon, it was important to share the data products with the review committee and discuss sensitivity to concerns, such as the inherent meaning of color values (e.g., green meaning “ready for development”). The decision was made to present the visual resource overlaid in shades of gray, with hatched polygons overlaid for special areas. This visualization best represented the visual resource class values while helping to keep interpretation of their meaning neutral from a policy standpoint.

Results

High-value visual resource classes tended to correspond with the views from headlands and capes along the Oregon coast. These viewpoints are higher in elevation, which increases the distance that the viewsheds extend out to sea. This resulted in the highest-value views also having the largest area on the ocean categorized as high-priority areas for viewshed protection. The distribution of these high-value areas focused on the north and south coasts. Larger headlands and capes with miles of sandy beach that separate them dominate the north coast. The headlands tend to be protected parklands and have relatively well-developed access to the high points. The sandy beach areas tend to be locations of coastal communities. In the transition from the north to central coast, larger bays and estuaries emerge as a new feature. These bays and rivers contribute to the visual value, although increased human impacts along these features are also found inland along the waterways that have lower-intensity urbanization. The geological pattern changes on the south central coast, from the prominent headlands at Cape Perpetua followed by a large area dominated by dune fields. Here, the visual scores also decreased, along with the more simplified natural landscape; and the elevations decreased, reducing the extent of the views out to sea. This dunal area then transitions again close to Cape Arago, where the coastal mountains and coastline become closer together and the larger rocky headlands reemerge as the dominant feature. In this southern portion of the coast, the coastline is primarily rocky, with steep headlands and offshore rocks. This landscape again increases the scenic quality ratings, although developed access to high points is not as common so the extent of views out to sea is not as great as on the north coast.

Figure 15.5 presents the composite map that shows the total extent of views that are cataloged in the C-MAAR application. These viewshed values are taken from the field, before the different distance zones are applied. Once the scenic quality ratings are applied, this map provides a weighted density of the views, as the higher-scoring views increase the value of the associated areas for mapping display purposes. Multiple overlapping, highly rated views create the darkest hues in the figure. Figure 15.6 is a bar chart presentation of the distribution of scenic quality ratings by viewpoint and depicts the underlying scenic quality factors that contribute to the overall rating. The final map output from the model is the composite scoring map with distance zones applied and shows the maximum value selected for any given area. Figure 15.7 is the adopted policy map for the TSP update and will be the starting point for future permit reviews when proposals are evaluated for potential visual impacts within areas of state jurisdiction.

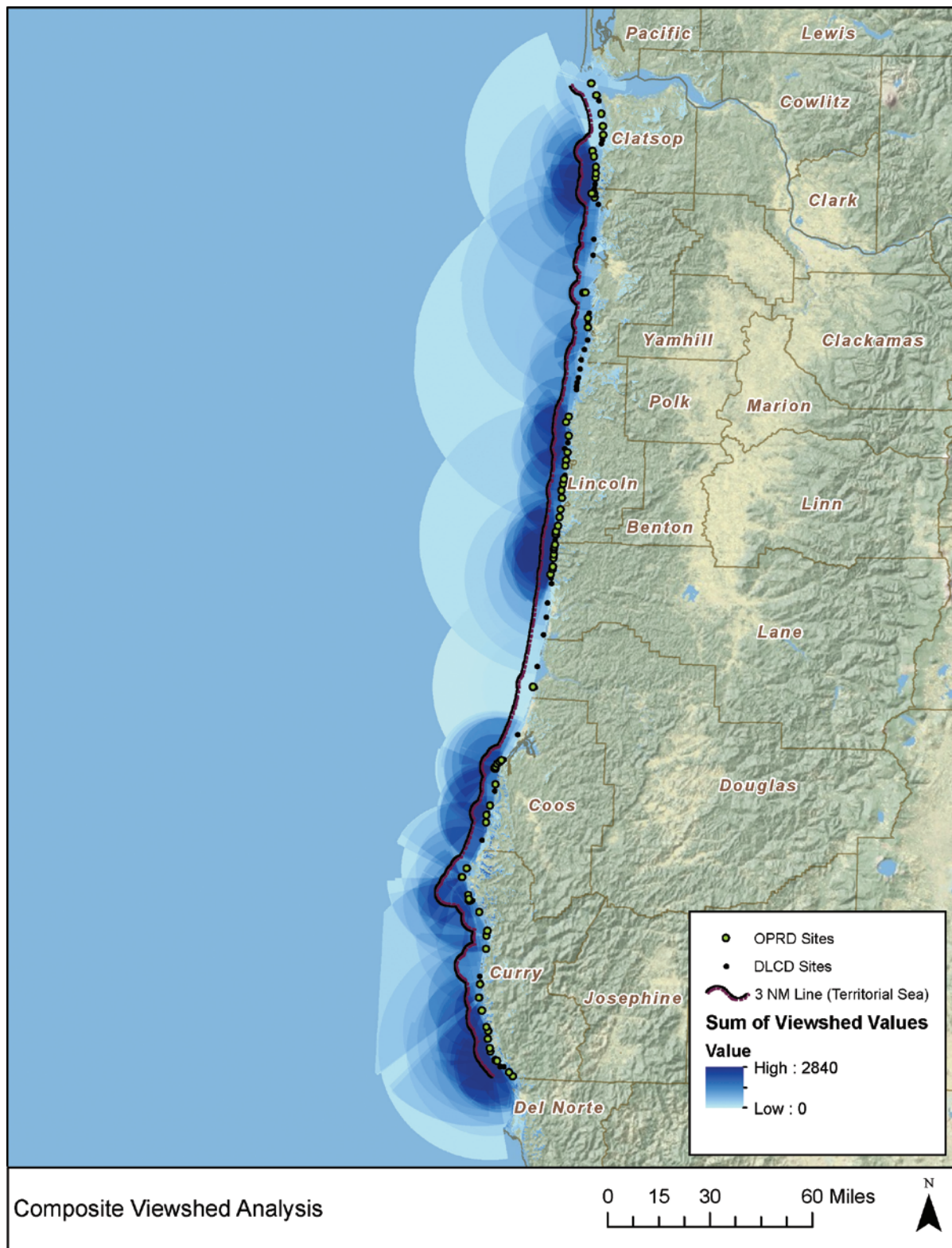


Figure 15.5. Final composite viewshed scores and extents, with the value depicted as the total score of all overlapping assessments, which illustrates the density and value of the views along the coast. Data sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors.

Territorial Sea Scenic Quality Evaluation Scores*

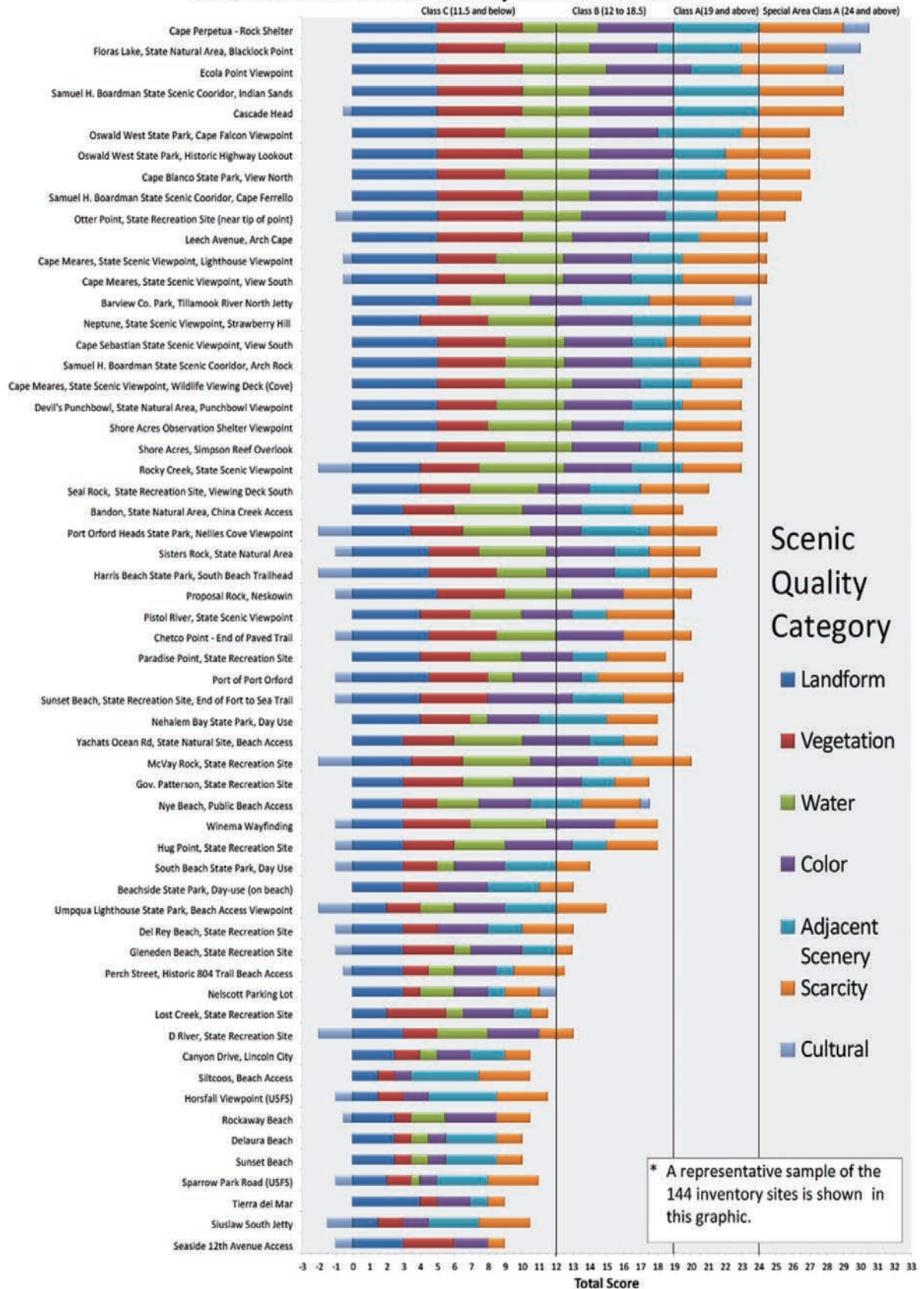


Figure 15.6. Results from the C-MAAR application on the Oregon coast.

Oregon Territorial Sea Plan Visual Resource Class Map

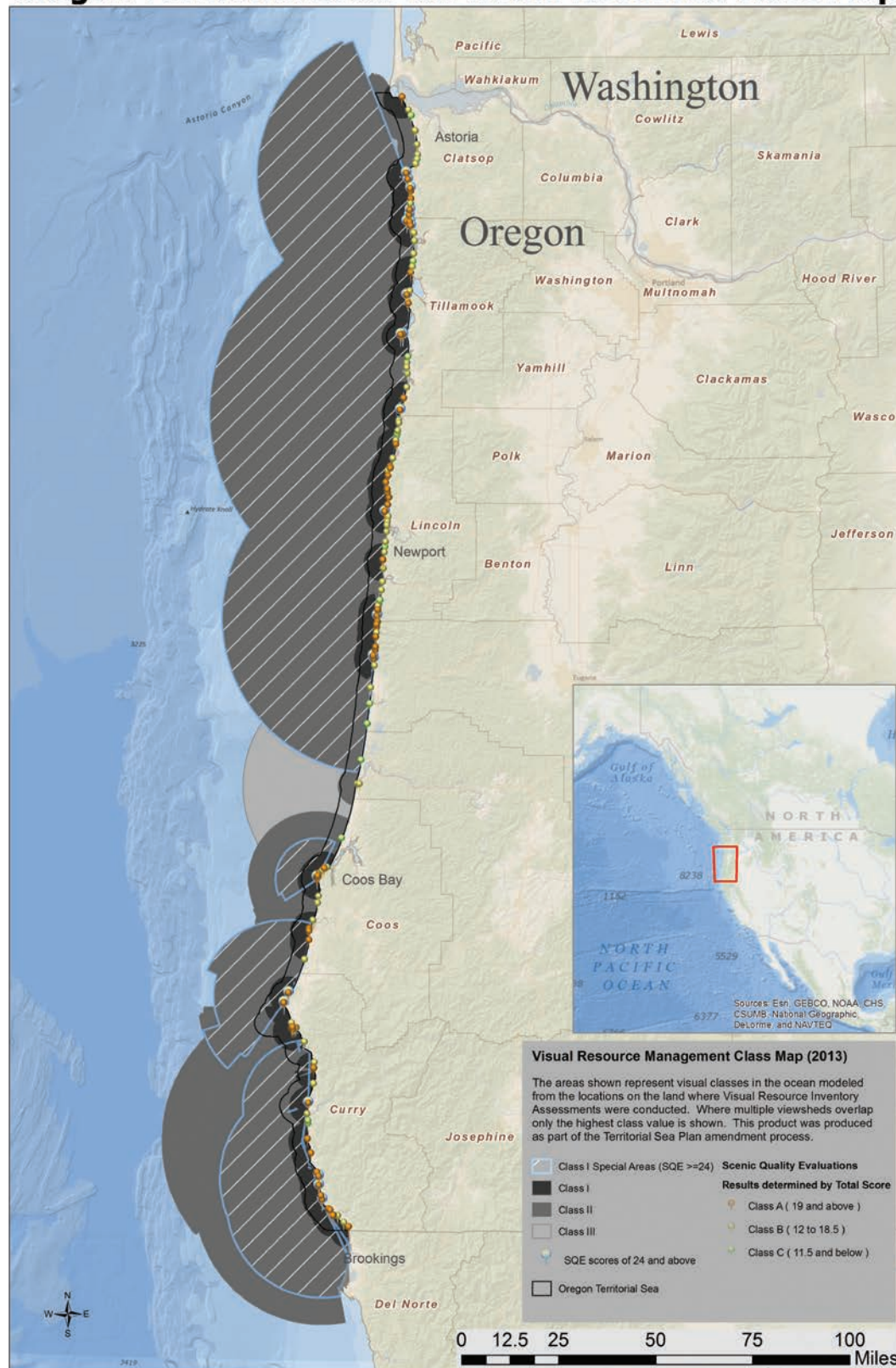


Figure 15.7. Final visual resource management class map produced by C-MAAR. Data sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors. AND Inset map data sources: Esri, GEBCO, NOAA, CHS, CSUMB, National Geographic, DeLorme, and NAVTEQ.

The final viewshed map is the composite of the overlapping views, with the maximum class displayed for any given area. This grouping resulted in a very large area of high-value classes. The prominent headlands and capes along the northern half of the coast all scored highly, and some were designated as special areas. Similar to the south, the steep headlands and cliffs produced large viewshed areas with high values. Upon initial review, this classification appears to create a uniform application of the highest-level view classification within Oregon's territorial sea. The committee charged with developing this model set policies that tended toward a more expansive definition of important views. This expanded definition reflects a key value for the Oregon coast.

Several areas stand out as potential opportunities for marine renewable-energy development from a viewshed perspective. In the north, near the community of Astoria, a large section of territorial sea is in a class B ranking, which permits development as long as it does not dominate the view and only minimally attracts attention. This area is also a focus area for potential development because of its proximity to a large port, land-based infrastructure, and a potential power purchaser. Farther to the south, two more class B and one class C areas emerged from the analysis. These areas also meet other requirements for development of marine renewable energy. The viewshed classes are the starting point for reviewing permit applications. Applicants for marine renewable-energy projects will be required to complete visual impact analyses, including visual simulations of their intended development, and contrast evaluations from the key viewing areas. This analysis will be reviewed by a joint agency review team (JART) and compared relative to the class standards included in TSP. If the applicants are able to demonstrate that their technology meets the intent of the visual resource standards for potentially affected viewpoints, the development will be allowed to proceed, at least on visual resource grounds. For example, a development is possible in the viewshed of a special-area view as long as the applicant can show that it will not change the view or attract attention, which is an easier task for distant developments offshore.

Since many types of technology are currently under development, and the project reviews will be both technology- and location-specific, this model and associated standards allow the flexibility to pursue technology development in a precautionary fashion. The data from the C-MAAR application supported many of the initial concerns about the location of high-value visual resources. This analysis was an important validation of the tool's use. The tool also identified areas for development that allow for a continued exploration of opportunities for marine renewable energy in Oregon.

Discussion and Conclusion

The C-MAAR application in Oregon presented a new opportunity to engage the public and stakeholders in a challenging resource evaluation. Visual resources are often defined complexly across communities, and coming to an agreed-on evaluation requires broad engagement and transparent tools. The Oregon experience suggests a path forward using an expert-based modeling system that engages a participatory field survey and codevelopment of methodology. In this final section of the chapter, we explore the implications of this tool for marine renewable-energy developers, discuss the strengths and weaknesses of the model, and offer an assessment of the model's ability to face the challenges we identified in the literature on visual resources and decision-making.

The Oregon TSP update has resulted in a set of policies captured in spatial data for the use and management of the territorial sea. Moving forward, future energy developers will make their permit applications to the State of Oregon, and the data produced in the update will be part of the review. The visual resource inventory from the C-MAAR application is a starting point for developers. The permit process will ask for more detailed visual simulations based on the specifics of the

devices that are proposed for use in the water. In this way, the model results from C-MAAR are a general guide for steering interest and policy preferences. However, permitting may occur in areas with higher-value classes if the impacts can be demonstrated to meet the standards and objectives outlined in TSP.

One challenge in a standardized visual resource survey method is that the scoring criteria can focus values on particular areas based on the mix of attributes present. The C-MAAR application in Oregon focused on views that comprised complex colors, vegetation, water features, and steep relief or unique landforms. This mix of attributes resulted in the high-value areas being the dramatic cliffs, headlands, and capes on the coast. Some areas along the Oregon coast, notably the Clatsop Plains to the north and the extensive sand dune country along the south central coast, tended to score lower because of the dominance of sand and beach grass views. These areas also tended to be lower in profile and have less diversity in colors, textures, and vegetation. Yet they are beautiful places in their own right. Some public comments noted that these areas were uniquely special because of the “sea of beach grass” that stretches almost to the horizon. However, the committee and other reviewers felt that when the various components of a view were examined and the results compared, the more complex sites were thought of as being more valuable by visitors and residents alike. This value judgment is a persistent problem in valuing natural resources in any setting. Experiences and values concerning the environment are difficult to quantify, and some trade-offs of the values among sites are a necessary outcome of ranking views.

Similarly, field teams encountered challenges in agreeing on the impact of cultural resources and anthropogenic impacts to the view. In some cases, human activities contribute greatly to the view. Examples are the iconic lighthouses of the Oregon coast. These features are now just as definitive of the Oregon coast view as natural components. Other human activities were more challenging. One portion of the coast has a unique dory fishing fleet that is launched using pickup trucks to back into the surf and release the vessels from their trailers. This launching requires automobile traffic on the beach and includes other vehicles aside from the fishing fleet. Surfers, day-trip visitors, and others can drive on the beach and park vehicles. To some stakeholders and reviewers, this vehicle access is a great detriment to the view. To other stakeholders, notably local residents, the vehicles pulling fishing vessels on the beach help define the history of the area and do not detract from the view at all. They did not want to see these traditional uses lower the site’s score. This challenge was not easily resolved. The views from this area scored well, but not at the very top of the scale. At the end of the process, some discomfort remained, although these areas received the highest visual class ranking from overlapping views from adjacent viewpoints. This challenge highlights the fact that these quantification exercises never fully resolve the politics over views, nor should they. The visual resource inventory was not an effort to “quantify out the politics,” but rather to craft a common language for the politics of views and create opportunities to explore the politics involved (Sarewitz 2004).

A challenge for this process was making a distinction with participants between what the model presents as visible versus what might actually be perceived by a viewer in any future development. Analyzing visibility differs from analyzing perception. Although much of the territorial sea is visible from shore, a question remains as to what viewers may or may not perceive. One part of this challenge is the variable ocean and sky conditions common for coastal areas, especially places like Oregon. Sea state, fog, and precipitation can all reduce what is expected to be visible on the water at any given time. This model makes a conservative choice to use the best of sea and sky conditions as the baseline. From a policy perspective, this baseline is justified as these types of conditions are also some of the most important to sightseers, tourists, and local residents. Another perception component is related to the viewer. We anticipate that local residents are far more likely to note changes on the ocean, whereas visitors are less likely to notice devices such as wave energy floats. If visitors note these

devices, they may not know what they are without some interpretation or education. Further, there is also a distinct possibility that some viewers will find a new value in seeing the devices, just as marine traffic and navigational aids are desirable elements to some viewers.

Environmental controversies and the communities that they impact are often framed as problems of missing science. In these situations, the response can be to turn to expert-driven solutions, but these strategies can oversimplify problems and not improve the decision options. Local communities are often already actively producing their own information on options (Wynne 1992). Communities are then important partners in developing a better understanding of the natural and social systems that policy choices impact. Measuring and valuing the natural systems that society depends on calls for expanding expert-based systems to include stakeholder experiential values in research and practice (Daniel et al. 2012). The National Science Foundation (NSF) Advisory Committee for Environmental Research and Education claims that “place-based science” is at the heart of understanding “complex environmental systems, particularly in the 21st century” (Advisory Committee for Environmental Research and Education 2003, 63). The Oregon story affirms these findings. Striking a balance between the expert-driven model of assessing visual resources and the experiential model of participatory assessments was a goal of the Oregon C-MAAR application. This tool also wrestles with a tension between the academic (or research) interest to develop more certain or validated methods and the policy imperative to reach a decision, a tension that is apparent throughout this process. The model provides a quick and robust method for assessing views while at the same time allowing for the coproduction of this data with communities that rely on these views.

The success of the application of C-MAAR is based on two observations from the process. The first is the experience in the field with the evaluation teams. The mix of local representatives and state planning staff allowed for evaluations to reflect on the importance of the site and its context to the state. The teams tended to merge on values for the sites and with only limited disagreement on the scoring. Only one site had a dispute over the final value, and ultimately it was a site that had many disputes. The other basis for evaluating success was in sharing the findings with representatives and the public after the fieldwork was done. In these settings, the process allowed for a dialog to come to terms over different elements of the views. As noted in the introduction, this effort relied on “hybrid forums,” with a mix of actors, expertise, and concerns within the stakeholder committee (Callon et al. 2009). These forums are seen as opportunities to move from oppositional politics, of for and against, to an embrace of controversy in which learning and exploration can occur. We believe that by coproducing the visual resource method, this exchange of ideas was achieved and new understandings of the future of Oregon’s territorial sea were developed.

This assessment procedure does have limits. As a participatory approach, this tool does not claim to solicit feedback that can be generalized to a population. Surveys or assessments often sample a human population to solicit views that can then be accepted as representative of the perspectives of that community. For this tool, we chose to engage actors with a representative role. This decision was made for two reasons: practicality and the policy setting in which the assessments are made. Even with participatory GIS, concerns can arise that the expert role or technology used limits true participation (Lejano 2008; Wright et al. 2009). A recognized barrier to the success of participatory approaches has been the institutional and resource constraints that limit complete participation in GIS projects (Brown 2012). Gaining complete participation by the desired representatives was also a challenge because some did not have the time or resources to participate. This lack of full participation may limit the success of assessments. Nevertheless, the application of C-MAAR in Oregon relied on reporting detailed results to commissions and other officials for full-scale review to overcome this challenge. The Oregon planning experience has been highly collaborative, both by design and necessity. Oregon’s land-use law that governs decision-making for the TSP update

focuses on participatory approaches, and these approaches have become a cultural norm in Oregon planning processes. Additionally, the TSP update was limited in funding, requiring partnerships with nongovernmental organizations, communities, and user groups. These partnerships resulted in a networked model of public process, with many parties contributing to policy development.

This project extended many of the formal spatial tools used in CMSP to the social and public arena by inventorying a key component of how most visitors and residents experience the Oregon coast. Views along the coastline are something that defines the Oregon coast, supporting a thriving tourism industry, underpinning a deep sense of place, and building on a legacy of parks and recreation that is a strong part of the entire state's identity. These tools come with their own limitations and challenges. However, the C-MAAR experience in Oregon suggests that expert modeling tools can be paired with participatory approaches to coproduce data and findings that support durable policy agreements on the management of our coastal and marine resources.

Acknowledgments

We wish to acknowledge the stakeholder advisory committee members that were a part of the TSP update for their contributions to developing the method and participating in the field. Additionally, we thank the local city and county staff and representatives that joined field crews for assessments, as well as the staff from OPRD for their assistance in assessing all the sites. The comments and suggestions of two anonymous reviewers greatly improved this chapter.

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Supplemental Resources

Dawn J. Wright, ed.; 2016; *Ocean Solutions, Earth Solutions*, second edition; http://dx.doi.org/10.17128/9781589484603_15d

For the digital content that goes with this chapter, explained in this section, go to the book's online resources (esri.com/esripress-resources/ocean-solutions-2e). There, you can download the data. Links and QR codes for additional Oregon territorial sea resources are provided here.

Territorial Sea Evaluation Tools

The book resource web page provides a link to download the following toolbox:

- Chapter15Tools.tbx: the ArcGIS toolbox developed for visual resource assessments, DLCD Viewshed Model

C-MAAR uses ModelBuilder to automate the steps required to translate field assessment results into spatial data. For the user, the model provides an interface to enter assumptions about the height of the viewer and the energy device at sea. The user is also asked to identify the point feature class to run the C-MAAR analysis on. The model steps through the viewshed method for each point in the assessment dataset.

The first step for the model is to create random points within a buffered distance of the viewpoint. This step manages uncertainty in the elevation data. The model then runs the ArcGIS Viewshed tool for each of these random points and assembles them into a single viewshed extent raster.

When the viewshed analysis is completed, two map algebra steps are taken to apply the field data values and distance class values. The viewsheds have a basic value of 1. The field data results are multiplied against the viewshed. This step results in each of the viewshed areas having the total score from the field assessment. The next step is to transform these values so that the different distance classes are also in the score. The distance classes are foreground, midground, and background. Buffers around the viewpoint capture these distances and are converted into raster files. The raster values are then reclassified using 100, 10, and 1 for the three classes, where 100 is the foreground; 10, the midground; and 1, the background. These values are then multiplied by the viewshed values. Thus, a 27 value for the viewshed results in a 2700 value for the foreground, 270 for the midground, and 27 for the background. The logic of this system is to allow for analysis of overlapping values.

The final output is a viewshed for each point in the inventory, valued with the field score and distance classes applied. These viewsheds are then ready to be assembled into various composite analyses based on policy rules for the planning process.

The book resource web page provides a link to view the following chart:

- ChartData.pdf: Territorial Sea Scenic Quality Evaluation Scores

This chart presents the assessment scores from the field for each site included in the Visual Resource Inventory Assessment (VRIA). For each site, the constituent attributes included in the total value are displayed in a stacked horizontal bar. The constituent scores in the stacked bar are (from left to right): Landform, Vegetation, Water, Color, Adjacent Scenery, Scarcity, and Cultural. The score threshold for classes A, B, and C is shown across the top of the chart.

Additional Oregon Territorial Sea Resources

URLs and QR codes are provided here for the following resources:

- Story Map app: Oregon Territorial Sea Plan – Visual Resource Scenic Quality Class Map, at http://oregonocean.info/AGO_shortlist_StoryMap/index.html



This interactive map provides each of the locations assessed in VRIA. Each point is also a link to a pop-up window that includes a brief description of the site, a panoramic photo taken during the assessment, the final score, the viewshed evaluation category, and a unique identifier code for the site.

- ArcGIS Online Map: Visual Resource Management of the Oregon Territorial Sea, at <http://geo.maps.arcgis.com/home/item.html?id=bd285e90714544d5882a5a78dbf179ad>



This online map displays the spatial outputs of VRIA. It is the composite viewshed map for use in managing the ocean off the Oregon coast. It includes the different distance-based viewshed scores and shows the extent of various views, how overlapping values are reconciled, and the final Viewshed Scenic Class Values. Map courtesy of the Oregon DLCD OPRD.

CHAPTER 16^{Updated}

Near Real-Time Oceanic Glider Mission Viewers

Shinichi Kobara, Christina Simoniello, Ruth Mullins-Perry, Ann Elizabeth Jochens, Matthew K. Howard, Stephanie M. Watson, Robert Currier, Barbara Kirkpatrick, and Stephan Howden

Abstract

The data portal of the Gulf of Mexico Coastal Ocean Observing System Regional Association was designed to aggregate and integrate data and model output from distributed providers and offer these, and derived products, through a single access point in standardized ways to diverse users. The portal evolved under funding from the US Integrated Ocean Observing System program led by the Interagency Ocean Observing Committee. Since 2013, the regional association has participated in six projects with multiple different glider platforms for near real-time trajectory monitoring and interactive data display. These projects include testing the feasibility of using the Liquid Robotics Wave Glider to study ocean acidification and tropical cyclones, hypoxia over the Texas-Louisiana Shelf, harmful algal bloom near the Florida west coast, and hurricane forecasting using multiple autonomous underwater vehicles.

The first project, led by the University of Southern Mississippi, was a 36-day mission supporting the Ocean Acidification Program of the National Oceanic and Atmospheric Administration. The goals were to demonstrate that the wave gliders are suitable autonomous surface vehicle platforms to monitor ocean-atmosphere fluxes of carbon dioxide and give the regional association the opportunity to develop automated workflows for Liquid Robotics glider data. The second project involved two deployments of a subsurface profiling Slocum G2 Glider (200 m) provided by Texas A&M University's Geochemical Environmental Research Group: the first during a portion of the August 2013 "Mechanisms Controlling Hypoxia" cruise conducted by the university's Department of Oceanography and the second for about 30 days in October. The goals of these initial deployments were to (1) test the feasibility of collecting temperature, salinity, and dissolved oxygen data near the seabed in relatively shallow (20–40 m) water; and (2) compare, validate, and merge cruise data with a glider's information. In the following years, multiple gliders were deployed simultaneously and shown in a single mission viewer.

One important outcome was the development of a web map app using the GIS platform to show data acquired from the glider deployments. Because data from the projects was not directly reported to a Gulf of Mexico Coastal Ocean Observing System server, the regional association had to retrieve and reformat the data to make it GIS-ready. Using geospatial technologies and Python scripts, a time-aware glider-track layer was automatically generated in an enterprise database and updated in near real time. This process has been applied to visualize near real-time observations from all glider platforms in the Gulf of Mexico.

Introduction

Stommel (1989) predicted that unmanned vessels would someday continuously survey the world's oceans while daily transmitting data to researchers. This prediction is well on its way to becoming a reality with the increasing number of autonomous vehicle technologies and international deployments (e.g., Glenn and Schofield 2009). Underwater gliders, also known as *autonomous underwater vehicles* (AUVs), offer a means to collect in situ ocean data from a wide range of sensors at a relatively low cost compared with conventional methods, such as vessels and mooring arrays. AUVs can be buoyancy driven or propeller driven and can fly underwater in a sawtooth pattern, collecting horizontal and vertical profiles of hydrographic conditions (Rudnick et al. 2004; Alvarez et al. 2007) (figure 16.1).

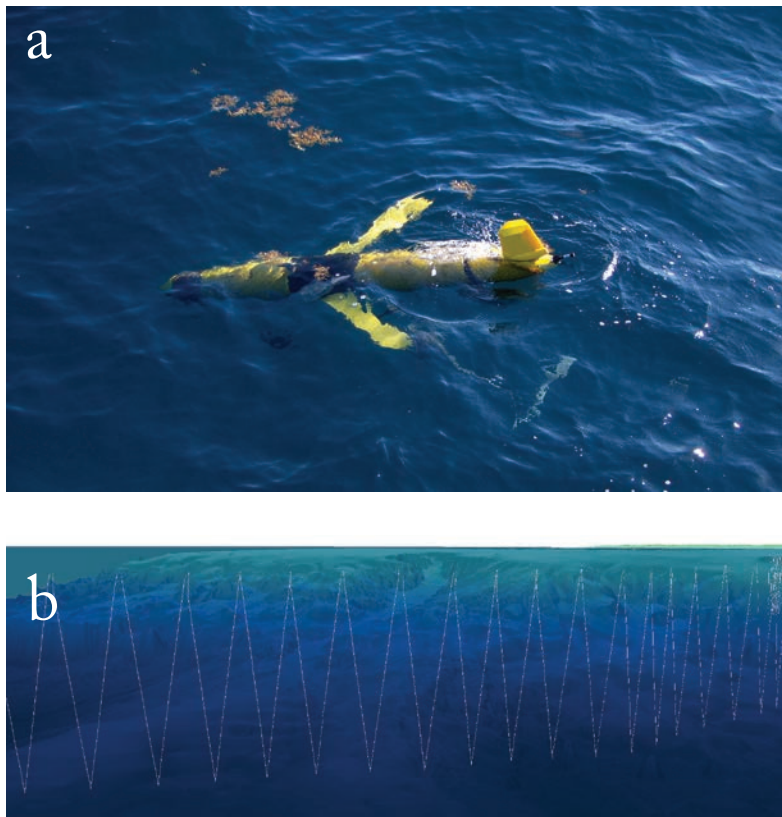


Figure 16.1. (a) Teledyne Webb Research Slocum G2 Glider. (b) The autonomous underwater vehicle's sawtooth movement underwater in the northern Gulf of Mexico. Photo by Eddie Webb (Texas A&M University Geochemical and Environmental Research Group).

More recently, wave gliders, the first unmanned autonomous surface vehicles (ASVs) to generate propulsion using the ocean's endless supply of wave energy, have been deployed as platforms from which surface ocean data is gathered and communicated in near real time (figure 16.2). Together, the AUV and ASV platforms offer unprecedented opportunities to observe and understand the world ocean.



Figure 16.2. Liquid Robotics Wave Gliders, a type of autonomous surface vehicle. Photo courtesy of Liquid Robotics.

Increasingly, glider development is moving toward plug-and-play capacity so that the platforms can carry varied and interchangeable instruments to measure and evaluate different oceanographic and air-sea interface attributes. In other words, sensors on the glider can be swapped out for different measuring devices, depending on the needs of each mission.

Data from these mobile platforms is expected to contribute significantly to the growing demand for sustained observations, to address issues ranging from climate change and severe weather forecasts to ecosystem management and water-quality monitoring. For example, boundary currents such as the Gulf Stream along the Eastern Seaboard pass near the coastal ocean and are important drivers of climate change (Williams 2012). In the Gulf of Mexico, the Loop Current and its associated eddies dominate mesoscale circulation (Hurlburt and Thompson 1980; Gopalakrishnan et al. 2013) and influence the potential strength and track of hurricanes entering the Gulf. Gliders in the coastal and nearshore environment also serve many interests that are specific to understanding the exchange of water between the coast and continental shelf. For example, freshwater runoff and coastal currents can act as physical controls and drivers of the dispersion of pollutants (e.g., nonpoint source, oil),

harmful algal blooms (HABs), and the extent and duration of hypoxia events resulting from low levels of dissolved oxygen on the ocean floor.

Expanding the use of gliders in the Gulf of Mexico is a necessary step in providing the geographical coverage, adaptive response, and long-term data needed to support science-based decisions regarding the ecological health of the Gulf. Successful expansion can best be achieved through collaborative partnerships. It is critical that the Gulf glider community be prepared to develop the Gulf glider network according to the needs of Gulf stakeholders. The US Integrated Ocean Observing System (IOOS) program (National Ocean Service 2014d) has embarked on an effort to outline a National Glider Network Plan (National Ocean Service 2014a). The US IOOS regional associations and partners are heavily engaged in glider operations and, in many instances, leading the way on their uses and mission applications. This chapter describes, in the context of the National Glider Network Plan, the current status of the Gulf of Mexico Coastal Ocean Observing System (GCOOS) and the Gulf of Mexico Coastal Ocean Observing System Regional Association (GCOOS-RA) Gulf Glider Task Team with regard to acquiring, processing, and delivering ocean observing and monitoring data acquired from sensors on gliders.

The Gulf of Mexico Coastal Ocean Observing System

GCOOS-RA is one of 11 regional components of the US IOOS, a cooperative effort of federal and nonfederal entities to provide new data, tools, and forecasts to improve marine safety, enhance the economy, and protect the US coastal and ocean environment (National Ocean Service 2014c) (figure 16.3). Because the Gulf of Mexico is a national ecological treasure and an economic driver for the country (Beck et al. 2000; Tunnell 2009), a delicate balance exists between environmental protection and economic development. All along the nearly 17,000 miles of shoreline from Florida to Texas (if bays and other inland waters are included), there are great demands from industries, including commercial and recreational fisheries, oil and gas exploration and production, ports, and tourism. The rich biodiversity of the region, combined with the dense human population, dictates that diligent monitoring take place to understand and protect the wealth of natural resources and protect human life and property.

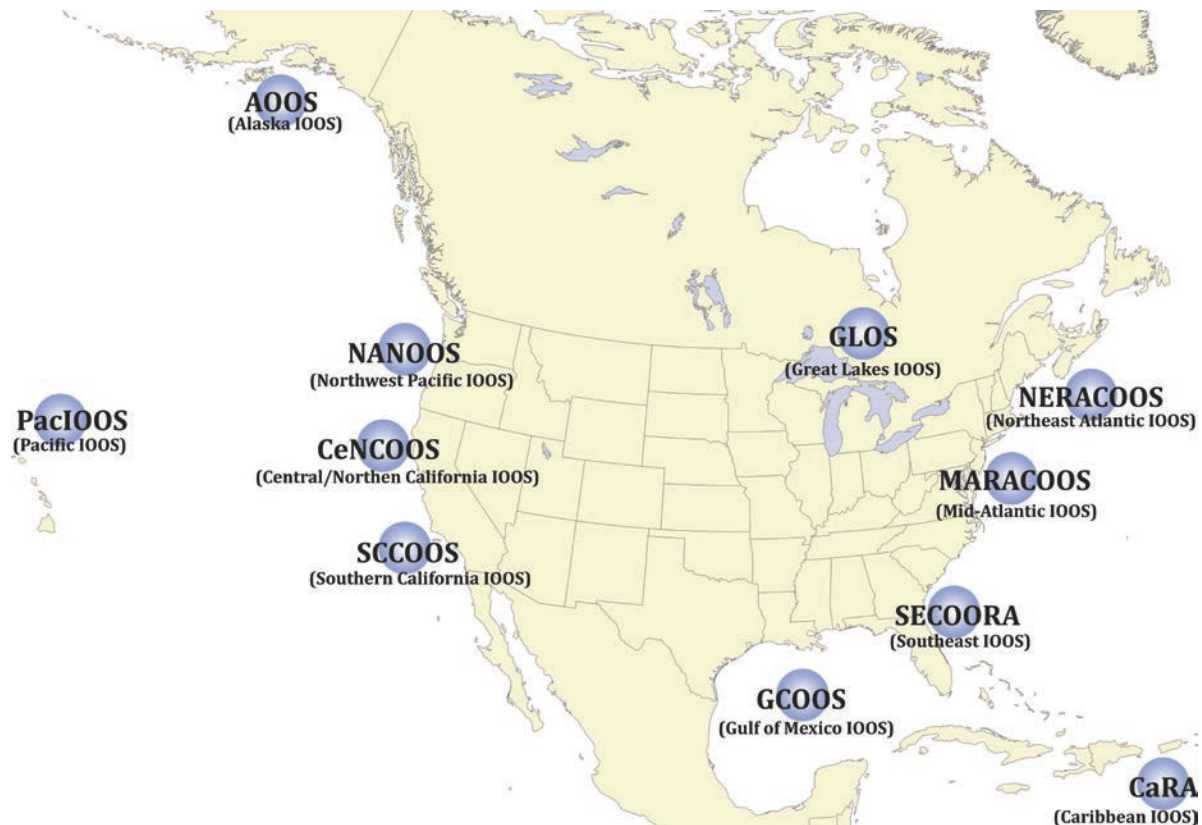


Figure 16.3. The US Integrated Ocean Observing System program has 11 regional associations that serve the nation's coastal communities, including the Great Lakes, Caribbean, and Pacific Islands and territories.

Since 2000, GCOOS has been growing toward becoming an integrated system of federal and nonfederal observing assets and data. Building GCOOS requires a partnership of many organizations, from governments to industry to academia to educators to the public, to integrate the measurements already being made and fill gaps where necessary to meet regional and national requirements. GCOOS-RA priorities are organized around themes that illustrate the broad, beneficial uses of observing system activities. Rather than invest limited funds in its own instrumentation, GCOOS-RA has maximized funds by leveraging existing nonproprietary private, local, state, academic, and federal assets to build GCOOS. The program is in the early stages of development, with clearly articulated plans for growth (see more details in a Build-Out Plan, version 2.1 [GCOOS-RA 2014e]).

On April 20, 2010, the Deepwater Horizon (DWH) oil spill tragically began in the Gulf of Mexico. GCOOS-RA contributions to the spill response effort were numerous and included the following:

- providing ready access to near real-time and historical data;
- creating new data layers for the Environmental Response Management Application (ERMA) tool used by the National Oceanic and Atmospheric Administration (NOAA) Office of Response and Restoration;
- delivering model results from the Regional Oceans Model System and wind forecasts;
- rapidly reinstalling high-frequency radar (HFR) along at-risk shorelines;
- providing web access to compiled oil spill resources; and
- conducting Gulf-wide education and outreach efforts to support effective communications about the spill (Office of Response and Restoration 2014).

In addition to GCOOS-RA, other IOOS regions contributed expertise during the DWH event, demonstrating the power of a coordinated network. GCOOS-RA, the Southeast Coastal Ocean Observing Regional Association (SECOORA), the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS), and the Southern California Coastal Ocean Observing System (SCCOOS) all collaborated and coordinated glider missions to identify and track the subsurface oil plume from the Macondo Well, from which DWH was operating. These IOOS partners deployed a fleet of seven AUVs with specialized sensors to help identify the presence of oil in the water column. The AUVs identified a search zone for the subsurface oil and helped define the likely movement of the oil. Temperature and salinity profiles were also acquired from sensors on the AUVs. This was the first known spill response effort to execute a coordinated multi-AUV operation.

An important contribution of GCOOS-RA was to convert AUV and float data from the DWH incident response site (National Oceanographic Data Center 2012) into map service layers for display on-site as well as for use in ERMA. These layers were two-dimensional, with metadata, including pointers to precomputed graphic displays of the associated profile data and the actual data. GCOOS-RA developed an interactive map to show the AUVs' tracks and temperature and salinity profiles at AUV surfacing (GCOOS-RA 2014a) (figure 16.4).

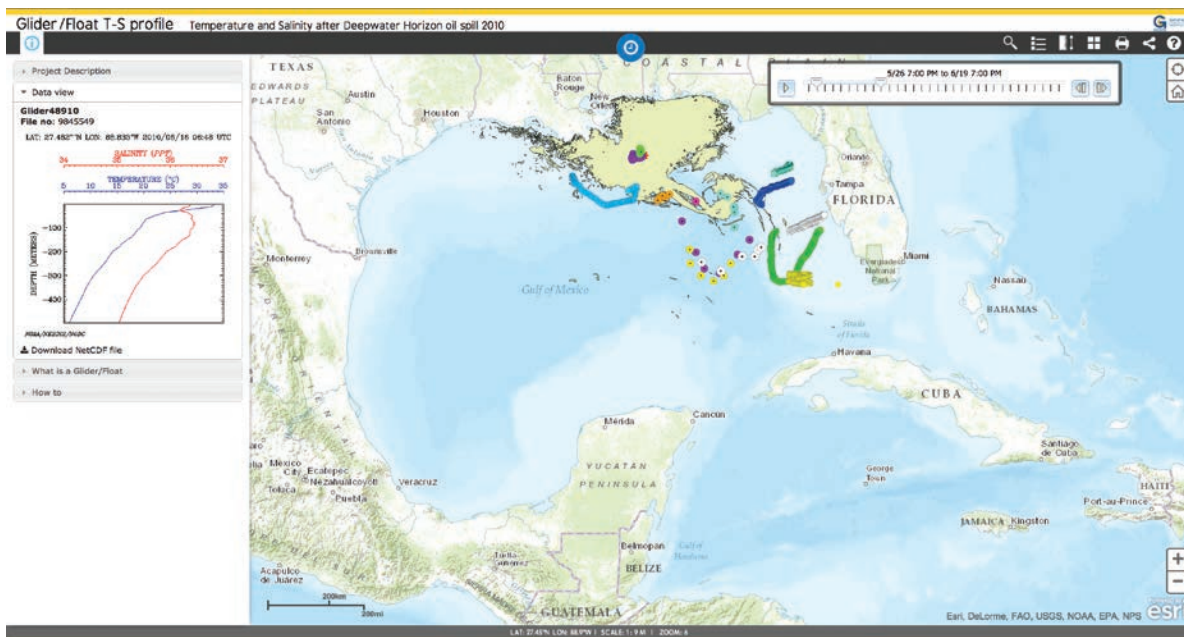


Figure 16.4. A web map app with a time slider displays the paths of gliders and floats as well as temperature and salinity profiles at their surfacing. This map product is part of the Gulf of Mexico Coastal Ocean Observing System Regional Association response to the Deepwater Horizon oil spill. Image courtesy of Gulf of Mexico Coastal Ocean Observing System. Map data sources: Esri, DeLorme, FAO, USGS, NOAA, EPA, NPS.

This interactive map provided time-aware AUV and float layers, which are stored information about the changing state of the AUV and float over time. This function allowed users to track AUV and float paths with a time slider. Despite important contributions to post-DWH monitoring, data processing, and information distribution, it was an ad hoc mapping system, one that would be greatly improved with a thoughtful infrastructure in place. The development of future monitoring plans must include such infrastructure.

The National Context for Gliders: The National Glider Network Plan

A combination of ocean-observing platforms and assets, each with different advantages for providing spatial and temporal information, can be collectively used to meet these needs. For example, ships can be used to operate high-power, full-bandwidth, high-resolution instruments to make observations and collect samples for various analyses, from the surface to great depths. However, because they are expensive to operate, most field campaigns using ships usually last for time scales of weeks to months. Also, the number of ships is limited, and they may not be available to respond quickly to events. Satellites make synoptic measurements over large areas of the ocean surface several times per day, but the measurements are largely limited to a thin upper layer or are related to information integrated over the water column (e.g., sea surface topography). Moorings provide persistent time series at 5- to 60-minute intervals over the water column at fixed locations and can acquire data for years. Gliders complement these traditional sampling methods well. The operation of gliders demands fewer man-hours relative to equivalent operations conducted using vessels, and gliders can be adaptively retasked and rerouted to fill data gaps, repeat a transect, or approach new targets of interest (Rudnick et al. 2004).

The IOOS National Glider Network is designed to function as a distributed system, with some centralized data management functions that apply consistent data standards and best practices to achieve integration among various glider-observing assets. As the lead federal agency for US IOOS, NOAA leads the overall plan and coordinates requirements and efforts to ensure consistency between national and regional needs and align the National Glider Network Plan with the national Data Management and Communication (DMAC) objectives. The associated national DMAC plan includes data from all glider operations and can serve this data to any user.

To date, three versions of AUVs have demonstrated persistent observations in an operational capacity: (1) Scripps Institution of Oceanography Spray gliders, now marketed through Bluefin Robotics (Sherman et al. 2001; Instrument Development Group of the Scripps Institution of Oceanography 2014); (2) the University of Washington Seaglider, now marketed through Kongsberg Maritime (Eriksen et al. 2001; Applied Physics Lab of University of Washington 2014); and (3) Teledyne Webb Research Slocum Gliders (Webb et al. 2001; Teledyne Webb Research 2010). All three have displayed robust reliability and fulfilled the missions outlined here. Collectively, over 500 of the three versions of AUVs have been manufactured and used. US IOOS is engaged in a collaborative effort to track where and when these missions occur.

The National Underwater Glider Network Map (National Ocean Service 2014b) includes current and historical glider missions dating back to 2005 and is a collaborative effort of GCOOS-RA, SCCOOS, MARACOOS, the Northwest Association of Networked Ocean Observing System (NANOOS), and the Central and Northern California Ocean Observing System (CeNCOOS). US IOOS, NOAA, the Office of Naval Research (ONR), National Science Foundation (NSF), Environmental Protection Agency (EPA), and various universities, state agencies, and industries have funded the gliders displayed on the map.

The National Glider Network Plan provides several examples of specific issues that have benefited from subsurface data provided by AUVs and explains how these issues will further benefit from a national network. These include

- emergency response (e.g., the dispersion of oil spills by currents in the Gulf of Mexico);
- climate variability, including El Niño/La Niña in the California Current System, the Loop Current in the Gulf of Mexico, and the Gulf Stream along the US East Coast;

- hurricane intensity forecasting, relevant for the East Coast, Gulf of Mexico, and American territories;
- HABs throughout US coastal waters; and
- hypoxia (low dissolved oxygen in bottom water), particularly in the northern Gulf of Mexico.

The GCOOS Approach with Gliders

Glider observations for the Gulf of Mexico are becoming increasingly vital for responding to the issues identified in the National Glider Network Plan. In response to this need, GCOOS-RA is bringing together representatives from academic institutions, government organizations, and the private sector to plan and implement a glider network in the Gulf. Coordination began in 2011 through the development of the GCOOS Glider Plan, a component of the comprehensive GCOOS Build-Out Plan. In April 2013, GCOOS-RA assembled a team of Gulf glider experts and created the Gulf Glider Task Team (GGTT) to further develop the strategic and implementation plans for Gulf glider operations delineated in the GCOOS Build-Out Plan. Elements of the National Glider Strategy are also being incorporated.

The National Glider Plan calls for a set of two to three glider transects in each regional association domain. This strategy meets some, but not all, the needs of glider operations in the Gulf. Glider pilot projects and partnerships between GCOOS-RA and stakeholders include collaborative strategies for detection of harmful algal blooms, monitoring ocean acidification (OA), monitoring hypoxia, routine measurements of water quality, and advancing a wide array of Gulf research.

In 2005, GCOOS-RA began developing the GCOOS Data Portal (GCOOS-RA 2008a), designed to aggregate observational data and model output from distributed providers and offer these, and derived products, through a single access point in standardized ways to a diverse set of users. GCOOS also has an associated Data Products page (GCOOS-RA 2008b) featuring products fused with data tailored for specific or general stakeholder groups. The goal of the GCOOS-RA in offering the Data Portal and data products is to provide an automated, and largely unattended, data system that delivers high-quality data and products to Gulf stakeholders.

Because geospatial data already includes dozens of file formats and database structures, and continues to evolve and grow new types of data and standards, flexible and customizable automated data flow is required for real-time and near real-time tracking systems. The Data Portal is custom built and includes web services based on the Open Geospatial Consortium (OGC) standards-based Sensor Observation Service (SOS) with observations and measurements (O&M) encodings. Products offered on the Data Products page are primarily map apps constructed using the ArcGIS platform.

Data access is through an online form and, for machines, is through a direct-access uniform resource locator (URL), Open Source Project for a Network Data Access Protocol (OPeNDAP), or an SOS access point. GCOOS designs web-based mission viewers for ASVs and AUVs using the ArcGIS platform. Web-based mission viewers run in near real time when stakeholders' gliders are operating in the Gulf and in playback mode after a completed mission. Viewers show the glider trajectories and oceanographic data that is collected and is publicly available through the GCOOS website.

The mission viewers were developed for the following four glider projects:

1. AUVs monitoring for subsurface oil following the DWH oil spill incident (GCOOS-RA 2010a);
2. Slocum gliders (AUVs) monitoring HABs, particularly the dinoflagellate *Karenia brevis* in southwest Florida (GCOOS-RA 2010b);

3. Pilot project 1, a wave glider (ASV) monitoring OA in the northern Gulf of Mexico (GCOOS-RA 2014b); and
4. Pilot project 2, AUVs being tested in the western Gulf of Mexico (GCOOS-RA 2013).

Autonomous Underwater Vehicle Monitoring Harmful Algal Blooms

GCOOS-RA partners at the University of South Florida (USF) College of Marine Science and Mote Marine Laboratory (MML) on coordinated glider missions to gain a better understanding of the dominant Gulf of Mexico red-tide organism *Karenia brevis*. The science mission used tandem AUVs to map the West Florida Shelf region with an emphasis on catching a red-tide bloom in progress to gain a better understanding of how to forecast and track harmful algal blooms. One specific project focus was to determine the abundance of *K. brevis* at the pycnocline because previous work suggested the cells might be concentrated there.

In typical use, AUVs profile from the surface to 500 to 1,000 m, taking three to six hours to complete a cycle from the surface to depth and back. During the cycle, the AUVs travel 3 to 6 km horizontally for a speed of about 1 km/h. Deployments of three to six months are routine, during which the AUVs' survey track extends well over 2,000 km. Sensors on AUVs measure such physical variables as pressure, temperature, salinity, and currents; biological variables relevant to the abundance of phytoplankton and zooplankton; and ecologically important chemical variables such as dissolved oxygen and nitrate.

During short surface intervals on the order of a few minutes, AUVs obtain location by GPS and communicate through the Iridium data telemetry satellite system. AUV data is transmitted to shore in near real time from that surface point, so an automated or semiautomated national distribution and archiving scheme is essential to making recently acquired and historical data readily available to a variety of users. At present, AUV data is received by servers at local data nodes and distributed in a variety of formats and through several protocols to GCOOS and/or a national system such as the National Underwater Glider Network Map (National Ocean Service 2014b).

The joint USF/Mote Marine Laboratory coordinated HAB glider mission was the first opportunity for GCOOS-RA to experiment with automated workflow and learn how to display glider data in near real time via the GCOOS website. GCOOS-RA developed a mission viewer to show the gliders' tracks collected at locations where the gliders surfaced to obtain position fixes and transmit data that had been continuously recorded in their data boxes (GCOOS-RA 2010b) (figure 16.5).

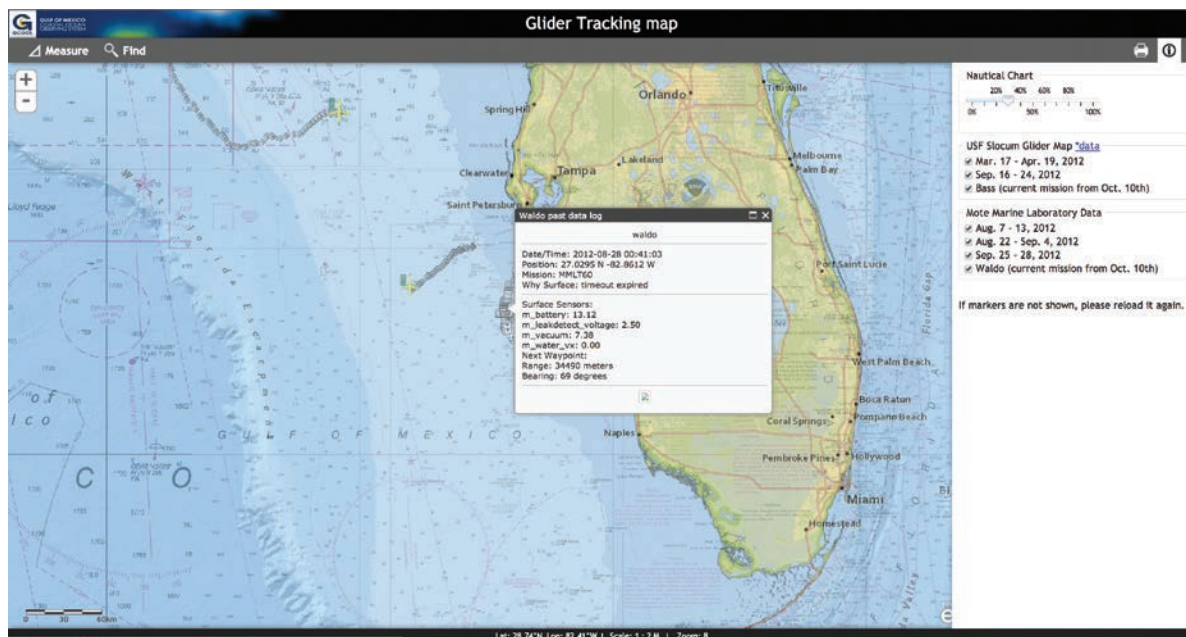


Figure 16.5. A mission viewer displays a glider's path and its system sensor information. Image courtesy of Gulf of Mexico Coastal Ocean Observing System (GCOOS). Data sources: Esri, GEBCO, NOAA, National Geographic Society, DeLorme, HERE, Geonames.org, and other contributors.

Pilot Project 1: ASV Monitoring of Ocean Acidification in the Northern Gulf of Mexico

Ocean acidification, or OA, is the ongoing decrease in the pH of the oceans, caused by the uptake of carbon dioxide (CO_2) as the atmospheric CO_2 concentrations rise (Caldeira and Wickett 2003). It is estimated that approximately 30% to 40% of the CO_2 released by humans into the atmosphere dissolves into the oceans, rivers, and lakes (Fabry et al. 2008; Doney et al. 2009). NOAA has initiated an active monitoring and research OA program (Ocean Acidification Steering Committee 2010). The principal goal of the program is to develop the monitoring capacity to quantify and track OA in open-ocean, coastal, and Great Lakes systems.

In an effort to investigate the feasibility of new technologies to monitor changes in ocean acidity related to CO_2 fluxes between the atmosphere and ocean in the Gulf of Mexico, the University of Southern Mississippi (USM), NOAA, GCOOS, and Liquid Robotics collaborated to deploy a Liquid Robotics Wave Glider (a type of autonomous surface vehicle) to measure CO_2 , dissolved oxygen, pH, water temperature, conductivity, air temperature, barometric pressure, and wind speed and direction in the northern Gulf of Mexico. The CO_2 sensor package, which measures the mole fraction of CO_2 on either side of the air-sea interface, was developed by the Monterey Bay Aquarium Research Institute.

The team successfully deployed the glider in October 2012 from the USM R/V *Tom McIlwain* near the USM Central Gulf of Mexico Ocean Observing System (CenGOOS), a subset of GCOOS. The location was selected so that the glider traverse started and ended at the CenGOOS buoy in the northern Gulf, which has a similar CO_2 measuring system developed and built by the Pacific Marine and Environmental Laboratory. The glider was programmed to run a route around the Mississippi River Delta and traverse over stations where the NOAA R/V *Ronald H. Brown* sampled in July 2012 during the second Gulf of Mexico and East Coast Carbon program. These additional observations

from the buoy and the ship-based sampling were used to help validate the measurements made from the ASV platform.

Wave gliders offer many sampling benefits. Among them are greater spatial coverage compared with traditional buoys, collection of data at different depths near the surface, the ability to travel anywhere without need of refueling, remote navigation and mission control, and the ability to transmit data via satellite anywhere in the world. Unfortunately, like other autonomous platforms, wave gliders are subject to collisions at sea. Such was the case during this mission when a vessel struck the wave glider at the southernmost part of its route on the 27th night. The USM and Liquid Robotics team retrieved and relaunched the wave glider in early February 2013 (figure 16.6).



Figure 16.6. The University of Southern Mississippi and Liquid Robotics team launch the wave glider in the Gulf of Mexico on February 12, 2013. Photo by Stephan Howden (USM).

Similar to the viewer previously shown for the DWH glider mission (see figure 16.4), GCOOS-RA developed an interactive near real-time mission viewer for the OA mission (GCOOS-RA 2014b) (figure 16.7), showing the glider's location and data from the mission. The mission viewer also displays time-series charts by parameter.

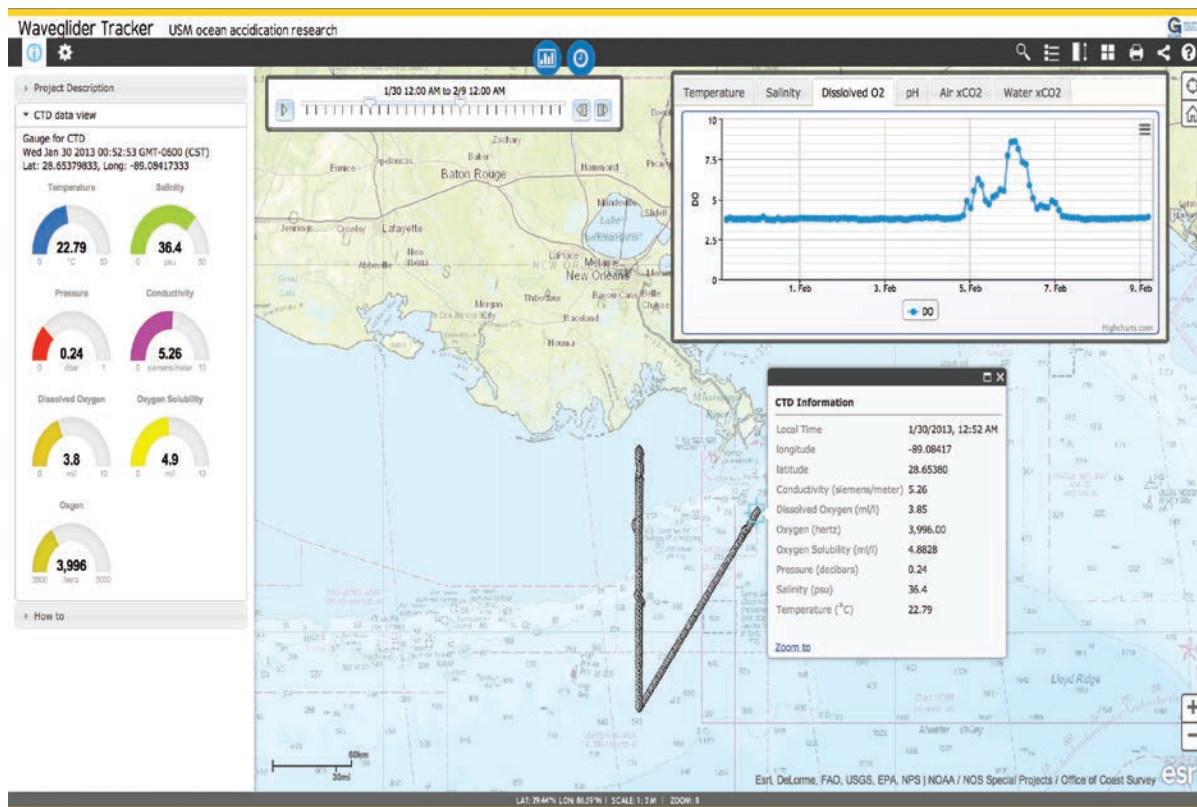


Figure 16.7. The wave glider mission viewer displays the glider's path and multiple observation parameters in a gauge and chart using a time slider. Image courtesy of Gulf of Mexico Coastal Ocean Observing System (GCOOS). Map data sources: University of Southern Mississippi (USM), Esri, DeLorme, FAO, USGS, EPA, NPS; NOAA NOS Special Projects Office of Coast Survey.

From aggregating data to showing updated sensor parameters every 10 to 20 minutes, several conditions were considered during development of the near real-time wave glider mission viewer. Lessons learned from a previous mission by IOOS partners guided development. In an earlier demonstration project, two IOOS regional associations, Northeastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS) and MARACOOS, had bandwidth problems for wave glider communications that led to failed initial attempts to establish a sensor observation service. Armed with this knowledge and knowing that the OA wave glider mission was short, all the data from the wave glider was telemetered to a Liquid Robotics server, without an automatic link to the GCOOS-RA server, thus bypassing the bandwidth issue.

As with any integrated observations, the heterogeneous devices and data formats create challenges for an organized data-storing process. In this case, there was no push system implemented, and a data aggregation system had to be built. Near real-time observations require a robust architecture from desktop to cloud, with a timely, extensible, and automated process. This situation poses similar problems that might arise in trying to add live weather or recent earthquake information to apps without writing long programs first. There are multiple approaches to tackle this challenge, but GCOOS chose ArcGIS 10.1 Tracking Server (predecessor of ArcGIS GeoEvent Extension for Server) for this project. ArcGIS 10.1 Tracking Server is an independent server and serves as the engine for processing and distributing real-time data to various clients via data links.

The process that GCOOS-RA created to integrate the observations is as follows: First, GCOOS-RA aggregated information from Liquid Robotics Server. Liquid Robotics provided the specific URLs to retrieve conductivity-temperature-depth (CTD), weather, oxygen, and system data. Each file contained sensor information, location (latitude and longitude in World Geodetic System 1984 [WGS84] datum), and time of collection, all in comma-separated value (CSV) file format. This process used simple Windows batch scripting and a handful of command-line utilities (cURL, wget) (Free Software Foundation 2012; Stenberg et al. 2014) to download automatically. Scripts were run every 10 minutes. For the ArcGIS Tracking Server to operate, it must know how the data is formatted and how it is being received. Following the aggregation of Liquid Robotics data, GCOOS-RA created a new message definition and new Generic Input Data Link connection based on a received file (Esri 2012a, 2012b). Once the data was saved to a folder, another script ran to format the data for each database schema configured in the tracking server and push the data into the tracking server through a transmission control protocol (TCP) socket. Although ArcGIS Tracking Server can convert/format data, in this case it focused on aggregating and logging data into an ArcSDE database. Esri provided C# and Java programs to send data through a TCP socket. GCOOS-RA created a simple Python script to do the same (TcpCommunication 2012). Four feature layers in ArcSDE database updated automatically every 10 minutes when new data was downloaded.

Although Liquid Robotics provided a web-based remote control system for the wave glider to give its current location, ArcGIS users can also see the glider location by connecting the tracking server in the ArcCatalog and ArcMap applications of ArcGIS. If users need real-time data viewing with analysis capabilities, the ArcGIS Tracking Analyst extension for ArcGIS for Desktop software allows users to display, analyze, and manipulate real-time and fixed-time data.

Once the data was logged into the ArcSDE database, the information was published through ArcGIS for Server as a mapping service. This whole process is shown in figure 16.8. Although ArcGIS Tracking Server is the engine for processing and distributing real-time data, a separate client application, such as ArcGIS for Desktop, is needed to view the data. GCOOS-RA developed a web map app, or glider mission viewer (GCOOS-RA 2014b), in the ArcGIS API for JavaScript application programming interface (API). The web-based app provides a common operating picture for monitoring and tracking an event. It has an interactive map, charts, gauges, and a time slider for scientific observing parameters (see figure 16.7). Basic functions such as a measurement tool, basemap catalog, print tool, and social sharing tool were also implemented.

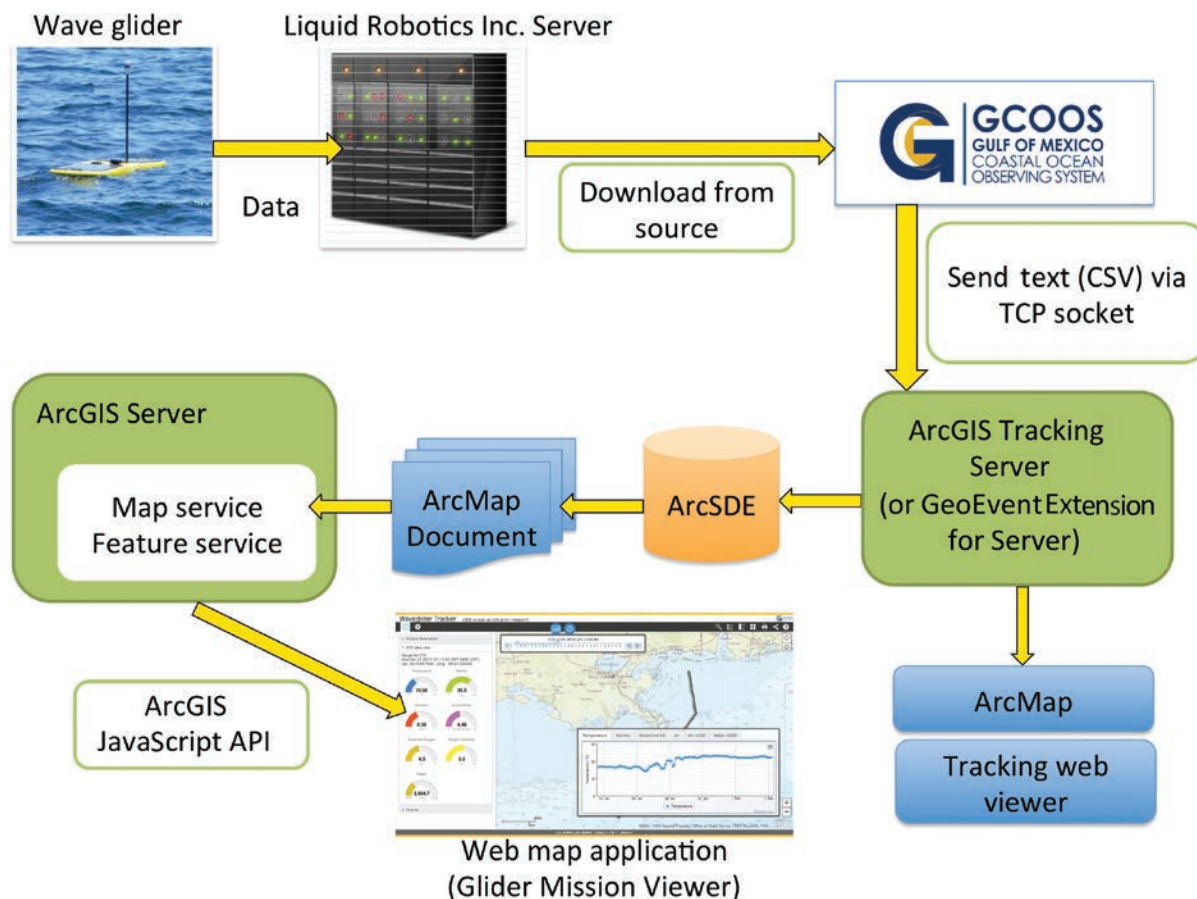


Figure 16.8. Diagram of the automated workflow for the joint University of Southern Mississippi/Liquid Robotics/GCOOS Ocean Acidification wave glider mission viewer. Image courtesy of Gulf of Mexico Coastal Ocean Observing System (GCOOS). Map data sources: NOAA NOS Special Projects Office of Coast Survey, Esri, DeLorme, FAO. Photo courtesy of Liquid Robotics Inc.

This mission viewer uses gauges to show near real-time temperature, salinity, pressure, conductivity, and dissolved oxygen values. Other wave glider engineering and meteorological information, such as wind direction and speed, is provided with an overlaid nautical chart. The layers are also downloadable in Keyhole Markup Language (KML), an Extensible Markup Language (XML)-based file format used to display geographic data in an Earth browser such as Google Earth, and are accessible to the data through feature services for use with ArcGIS (GCOOS-RA 2014c).

Pilot Project 2: Development of an AUV Mission Viewer for Testing

The Texas A&M University (TAMU) Department of Oceanography and the Geochemical Environmental Research Group (GERG) deployed a Teledyne Webb Research Slocum G2 Glider (200 m) during the Mechanisms Controlling Hypoxia (MCH) cruise in August 2013 (DiMarco 2013) and again over the Texas-Louisiana Shelf in October during a Texas Automated Buoy System maintenance cruise (figure 16.9). The AUV's mission was to test the capability of collecting temperature, salinity, and dissolved oxygen data over the shelf in relatively shallow waters of 20 to 40 m depth and collect hydrographic data near and around the Flower Garden Banks National Marine Sanctuary. In this pilot project, GCOOS tested a near real-time mission viewer compiled with underwater profiling information.



Figure 16.9. Pilot test of an autonomous underwater vehicle for hypoxia studies in the northern Gulf of Mexico by the Texas A&M University Geochemical and Environmental Research Group. Photo by Eddie Webb (Texas A&M University Geochemical and Environmental Research Group).

While at the surface, an AUV obtains location by GPS and communicates through the Iridium data telemetry satellite system. AUV data is received by the GERG shore station in near real time and stored in a folder dedicated to that particular AUV. Two types of files are created: (1) an AUV system health and trajectory information (SBD) file produced while the AUV is at the surface and (2) a scientific data (TBD) file containing sensor measurements made while the AUV is submerged. GCOOS-RA copied these files from the GERG web-accessible folder to a working folder, where they were processed into engineering units and basic products.

Trajectory files were processed using an Interactive Data Language (IDL) script to produce a cumulative file and daily file with the latest positional data. IDL software is often used in the analysis of one-, two-, and three-dimensional datasets. A cumulative file was also written in KML and made available to the IOOS map (National Ocean Service 2014b). Except for the processing of SBD and TBD files, the processes are almost identical to that of the wave glider. Files were processed four times per day in this project and sent to the ArcGIS 10.2 GeoEvent Extension for Server processor (upgraded from ArcGIS Tracking Server) and logged into an ArcSDE database.

Data files were processed, and graphic displays of measured parameters were produced and posted on the web. A mission viewer (GCOOS-RA 2013) showed the updated location of the AUV every six hours. Cumulative profile plots of temperature, salinity, and colored dissolved organic matter (CDOM) were also available on the mission viewer (figure 16.10). All AUV tracks are available in a KML file as well. The glider tracking layers are also downloadable in KML and accessible to the data through feature services to enable copying into a user's local environment (GCOOS-RA 2014c).

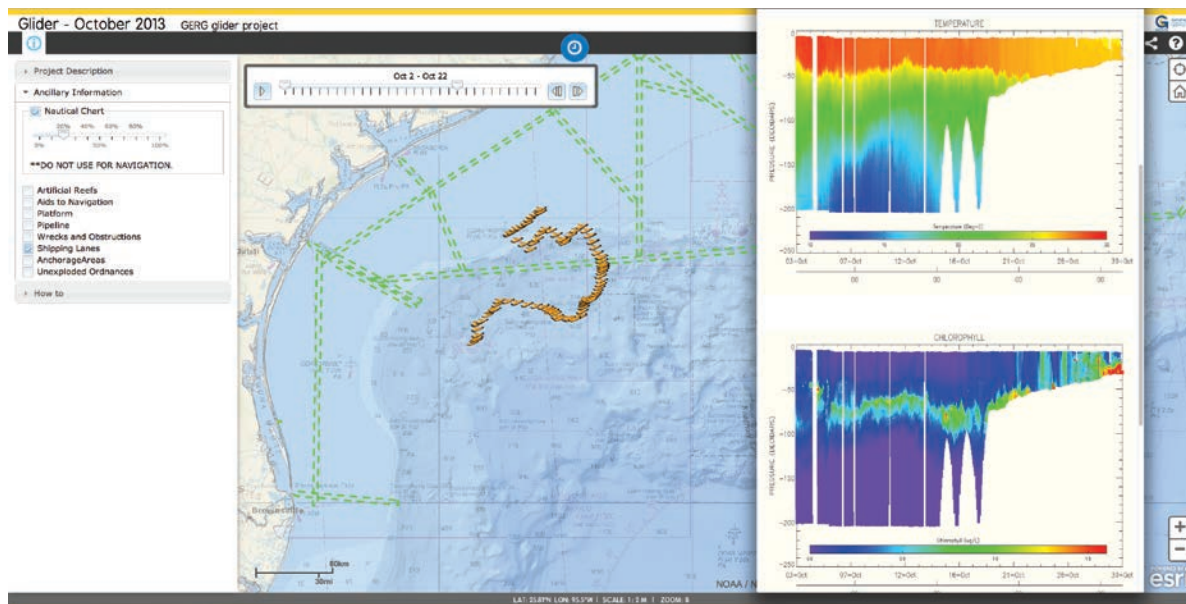


Figure 16.10. A mission viewer for Slocum profiling gliders being tested in the western Gulf of Mexico by the Texas A&M University Geochemical and Environmental Research Group. Image courtesy of Gulf of Mexico Coastal Ocean Observing System (GCOOS). Map data sources: NOAA NOS Special Projects Office of Coast Survey, Esri, DeLorme, FAO.

New Developments

Developing mission viewers for the AUVs and ASVs in the northern Gulf of Mexico pilot projects successfully demonstrated near real-time glider observations using ArcGIS web mapping APIs. These activities and resulting products were intended to validate data acquired from glider platforms, facilitate use of the information through user-friendly interfaces, and help establish a user-driven glider program that is responsive to Gulf of Mexico information needs. New developments include (1) using AUV data to improve hurricane prediction and forecasting models, (2) developing a mission viewer of ASV data to improve hurricane forecasting, (3) developing a mission viewer for AUV hypoxia monitoring, and (4) creating a new mission viewer for the 2015 AUV Jubilee.

AUV Data to Improve Hurricane Prediction and Forecasting Models

GCOOS-RA is partnering with Shell Exploration and Production Company and the NOAA National Data Buoy Center (NDBC) to improve hurricane prediction and forecast models with gliders. Details about the collaboration can be found at the GCOOS website (GCOOS-RA 2014d). Shell, NOAA NDBC, National Centers for Environmental Prediction (NCEP), IOOS, and USM are working together to operate AUVs (200 m and 1,000 m gliders) to collect real-time data to measure upper-ocean heat content in the Gulf of Mexico. The data collected from the AUVs is used to improve hurricane intensity predictions with the goal of improving real-time hurricane intensity forecasts. The project coincides with additional federal projects to collect measurements that are necessary for hurricane prediction, such as the deployment of airborne expendable bathythermographs (AXBTs), which measure temperature as a function of depth, from the NOAA Hurricane Hunter aircraft that monitor hurricane development and progress. The GCOOS-RA,

Shell, and NOAA NDBC collaboration includes data sharing and supports Gulf of Mexico stakeholder and community engagement, education, and outreach to promote hurricane research and monitoring.

Mission Viewer of ASV Data to Improve Hurricane Forecasting

In 2014, GCOOS-RA participated in a joint exercise with Mississippi State University (MSU), Liquid Robotics, and NOAA, which deployed three wave gliders leased from Liquid Robotics into the eastern Gulf of Mexico to provide data aimed at improving hurricane forecasting. The gliders collected data in three different areas and were shown in a single integrated mission viewer. The mission viewer and its data are available at GCOOS Products site (GCOOS-RA 2015a).

Mission Viewer for AUV Hypoxia Monitoring

During 2014 and early 2015, GCOOS-RA continued to work for hypoxia monitoring projects. Multiple AUVs were deployed in summer 2014 in different regions, in conjunction with shipboard hypoxia measurements from a cruise. All the AUVs have CTDs, fluorometers, and dissolved-oxygen sensors. GCOOS-RA operated a real-time trajectory monitoring mission viewer that showed the locations of all AUVs and multiple sensors' profile charts (GCOOS-RA 2015b).

Mission Viewer for 2015 AUV Jubilee

In the summer of 2015, GCOOS-RA joined the AUV Jubilee, which was an inaugural event to coordinate AUVs and other in situ ocean data operations in the Gulf of Mexico. GCOOS-RA collected AUV data from multiple participants, including Rutgers University, University of South Florida/Mote Marine Lab, Oregon State University, Skidaway Institute of Oceanography/University of Georgia, and Texas A&M University. GCOOS-RA gathered raw data from AUVs and generated KML and netCDF files to forward to the National Glider Distribution and Archive Center. The data was made available for public access through the NOAA Environmental Research Division Data Access Program (ERDDAP) and Thematic Real-time Environmental Distributed Data Service (THREDDS) end points. All data is integrated into a new mission viewer, the Gulf AUV Network and Data Archive Long-Term Storage Facility (GANDALF) (GCOOS-RA 2015c). All AUVs' trajectories and data are assembled, monitored, and archived through this mission viewer (figure 16.11). GANDALF is unique in that it provides both archival and real-time data visualization for AUVs deployed in the Gulf of Mexico. GANDALF is configurable on a per-vehicle basis, allowing principal investigators to choose sensors to be plotted, appropriate color maps, and the public name of the vehicle (e.g., "Stommel" versus "unit_541"). GANDALF's primary interface is a GeoJSON layered Leaflet map view. A dashboard display that features deployed vehicle progress allows users access to plots and an automatically updating Google Earth KMZ file.

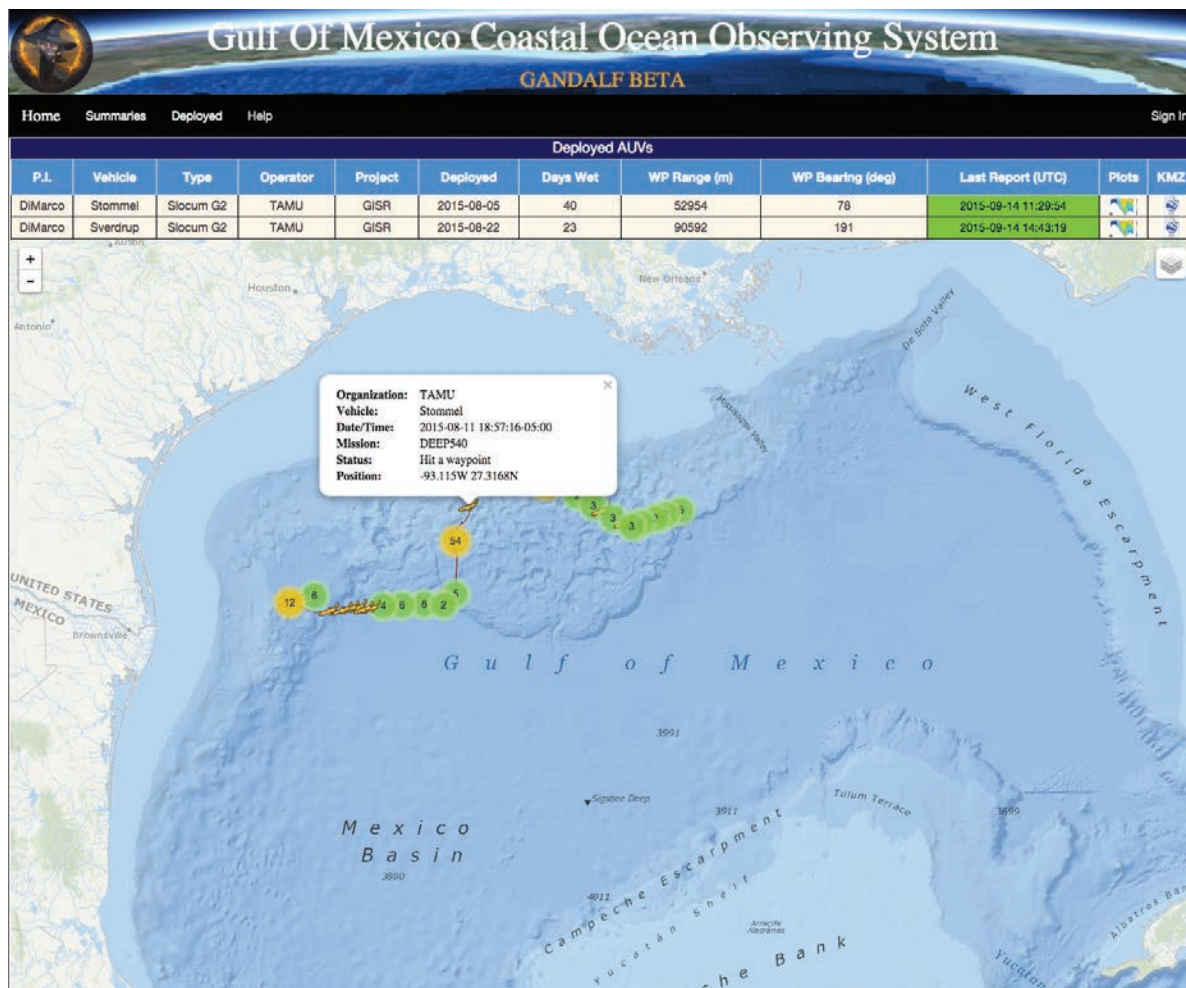


Figure 16.11. A mission viewer as of 2015: the Gulf AUV Network and Data Archive Long-Term Storage Facility (GANDALF) Group. Image courtesy of Gulf of Mexico Coastal Ocean Observing System (GCOOS). Map data sources: NOAA NOS Special Projects Office of Coast Survey, Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors.

Lessons Learned and Future Plans

GCOOS-RA will continue to broaden collaborations to advance the establishment of a comprehensive and continuous Gulf Glider Network and work with the US IOOS community on development of the National Glider Network Plan. In addition, GCOOS will continue working with operators and stakeholders to develop glider data visualization tools and products (e.g., three-dimensional visualizers, education and outreach resources, and profiling operations on the GCOOS website). Establishing a glider server and asset map simplifies the distribution process for glider operators and data users alike. Archiving this data in a repository will ensure its continued availability to all users.

Multiple collaborative projects described here demonstrate the expansive versatility of gliders as platforms to collect data for projects ranging from applied research to real-time environmental monitoring. Data collected by gliders is valuable to address a number of conditions. Among these benefits are high-resolution physical observations to better protect offshore oil and gas assets;

improved tropical storm intensity and trajectory forecasts to better prepare Gulf Coast communities; and observations to address additional hazards, ranging from natural and anthropogenic pollution tracking to accurately estimating volume and areal extent of hypoxia events. For gliders to reach their full potential in the Gulf of Mexico, continued development of partnerships, such as those described here, between industry, government, military, and academia is critical. It is the only way to further research and expand ocean-observing capacity in the Gulf of Mexico.

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Supplemental Resources

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For the digital content that goes with this chapter, go to the book's online resources (esri.com/esripress-resources/ocean-solutions-2e). Links and QR codes are provided here for additional ocean glider resources.

Python Script

The book's online resources provide a link to download the following script:

- Glider Time Track Python script to convert CSV file to KML

Additional Ocean Glider Resources

Additional resources on near real-time oceanic glider mission viewers include the following:

- GCOOS Data Portal, at <http://data.gcoos.org>



- GCOOS Products page, <http://products.gcoos.org>



- Wave glider data via ArcGIS for Desktop, http://gcoosmaps.tamu.edu/arcgis/rest/services/Glider/USM_Waveglider/FeatureServer or <http://bit.ly/1GtekWD>



or



- Shell Glider in Esri CityEngine web viewer, http://bit.ly/shell_sg553



- Tracking server reference: message definition, http://resources.arcgis.com/en/help/tracking-server/10.1/index.html#/Creating_Message_Definitions/00r6000000026000000 or <http://arcg.is/1fhxVQL>



or



- Tracking server reference: generic input data link connection, http://resources.arcgis.com/en/help/tracking-server/10.1/index.html#/Using_the_Generic_Input_Data_Link/00r600000000w000000



- Python reference: send a text via TCP socket, <https://wiki.python.org/moin/TcpCommunication>



CHAPTER 17^{New}

Multivariate Classification of Seamount Morphology: Assessing Seamount Morphotypes in Relation to Marine Jurisdictions and Bioregions

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Abstract

This chapter presents a global classification of large seamounts (>1 km in height) based on their physical characteristics. Multivariate analysis identified 11 seamount types on the basis of differences in area, height, peak depth, proximity to nearby features, and the area of steep slope (termed *escarpment*²). The distribution of these seamount types was examined in relation to the global ocean bioregions and marine jurisdictions. Differences in the distribution of the 11 seamount types were observed between ocean regions, with the North and South Pacific highlighted as hot spots of seamount diversity. Differences in seamount distribution were also observed between marine jurisdictions, with differences observed between the waters within national jurisdictions and the high seas.

To investigate the usefulness of this seamount classification for assessing existing management regimes and setting future management priorities, the seamount types present within the Clarion-Clipperton Zone in the eastern Pacific Ocean and Kiribati's marine jurisdictions were examined. In both cases, the seamount types represented within the existing spatial management efforts were assessed. It is shown that for some seamount types the management objectives were being met, but in general some seamount types were either underrepresented or not represented at all. The role of this type of classification in setting management priorities is discussed.

Introduction

Seamounts are important features of the ocean landscape and provide a range of resources and benefits to humanity. Seamounts are key locations for many fisheries resources (Morato and Clark 2008; Clark 2009; Pitcher et al. 2010), such as spawning grounds for orange roughy (Clark 1999) and aggregation locations for many pelagic species (Morato et al. 2008). They are known to support valuable mineral resources (Verlaan 1992; Banakar et al. 2007; Hein et al. 2010; Schlacher et al. 2014); and many seamounts have elevated biodiversity compared with surrounding deep-sea areas, including genetic resources, which may have commercial applications (e.g., pharmaceuticals). As demand for these resources increases, a need exists for focused management of seamounts because of the potential impact of such activities on seamount ecosystems (Althaus et al. 2009). An inventory of location and physical setting will advance the management of seamounts.

Numerous attempts have been made to identify the number and location of seamounts, with the results ranging from approximately 10,000 (Harris et al. 2014) to 14,000 (Wessel 2001; Kitchingman and Lai 2004) to 33,000 (Yesson et al. 2011). There are several reasons for such a broad range in the estimates of seamount numbers, including the lack of detailed bathymetric information and different definitions of what constitutes a seamount. For example, Becker and colleagues (2009) state that about 10% of the 600 million 1-km-grid cells in the Shuttle Radar Topography Mission 30 Plus (SRTM30 Plus) grid are constrained by one or more soundings. If the grid size is increased to 2 km, about 24% of the cells are constrained by one or more soundings. Smith and Sandwell (1997) state that in the worst-case scenario (i.e., where there are no soundings), the lowest resolution of the satellite gravity data is around 12.5 km. Thus many of the estimates of seamounts are based on satellite-derived estimates of bathymetry, which may have a relatively low accuracy. As global bathymetric models improve, the estimate of the number of seamounts will continue to be refined. For example, the latest global gravity models predict thousands of previously uncharted seamounts (Sandwell et al. 2014). Based on size–frequency relationships for larger seamounts, Wessel and colleagues (2010) predict over 100,000 seamounts of greater than 1 km in height remain uncharted.

Different studies have applied similar seamount definitions in different ways—for example, the estimates of Yesson and colleagues (2011) were three times higher than those of Harris and colleagues (2014). This discrepancy is mainly because of the inclusion of peaks along oceanic ridges (including the midocean ridges) as seamounts in the former classification, whereas Harris and colleagues used a more classic definition of seamounts as “conical in form” (IHO 2013). The distinction between ridges and seamounts is important because these landforms function differently in their response to currents. The acceleration of currents over an obstacle on the seabed is a function of the obstacle’s height in relation to the depth of water and of the obstacle’s orientation with respect to the current for nonsymmetrical features. Therefore, the larger a feature is with respect to the depth of the water, the more it will interact with currents and cause local flow acceleration (the absolute flow speed varying as a function of the speed of the ocean current being deflected). In this regard, currents interact differently with the conical shape of seamounts than they do with elongated ridges. The deflection of bottom currents along the crest of a ridge leads to enhanced connectivity among ridge crest habitats. There is no similar oceanic process that connects individual seamounts.

The minimum height required for a seamount also varies within the literature. For example, Hillier and Watts (2007) identified 201,000 seamounts with a height greater than 100 m based on global ship tracking data, whereas Wessel and colleagues (2010) speculate that there may be more than 25 million such features. A recent paper suggests that seamounts include any geographically

isolated topographic feature on the seafloor that is taller than 100 m, including ones whose summit regions may temporarily emerge above sea level, but not including features that are located on continental shelves or that are part of other major land masses (Staudigel et al. 2010).

However, accurately measuring the bathymetry of the deep oceans, in which many of these small features occur, still presents difficulty because of the technical limitations of the tools used to make the measurements. For example, the vertical resolution of the satellite-derived data used to develop the SRTM30 Plus bathymetry model is on the order of 100 m for the deep oceans (Smith and Sandwell 1997). For this reason, we use a more classic definition of a seamount adopted from the International Hydrographic Organization (IHO): “A seamount is a distinct generally equidimensional elevation greater than 1,000 m above the surrounding relief as measured from the deepest isobath that surrounds most of the feature” (IHO 2013). Seamounts are generally volcanic in nature. We also include guyots within this classification, with a *guyot* being a seamount with a comparatively flat top (2013).

One of the main drivers behind the identification and classification of seamounts is to improve the management and conservation of these features. This stewardship may include the management of deep-sea fisheries (Food and Agriculture Organization 2009), the development of networks of marine protected areas (Convention on Biological Diversity 2010), or the management of deep-sea mineral resources (Lodge et al. 2014). The management of marine resources increasingly embraces the principles of ecosystem-based management (Browman and Stergiou 2004; Halpern et al. 2008; Levin and Lubchenco 2008), as such information on the biodiversity of seamounts is also required in addition to number and location.

Yet very few seamounts have been surveyed, with the global census of marine life on seamounts, or CenSeam, estimating that fewer than 200 seamounts have been studied in any detail (Office of Marine Programs 2010). It is known that seamounts are not all the same and that they differ in form, size, depth, and location (Rowden et al. 2005). Different local environmental and biogeographic conditions result in different faunal compositions (Clark et al. 2010). For this reason, modeling and classification approaches have commonly been employed to help predict which seamounts are likely to support different communities (Rowden et al. 2005; Tittensor et al. 2009; Clark et al. 2011). Common modeling and classification approaches are based on a suite of environmental and physical parameters.

Physical surrogates such as depth, slope, and proximity are important factors for determining the structure of biological communities. For example, many species are confined to a specific depth range (Rex et al. 1999; Clark et al. 2010). Therefore, both the minimum depth (peak depth) and depth range (height) are likely to be strongly linked to the biodiversity of a given seamount. Slope is also an important control in the structure of seamount communities, from steep, current-swept slopes, which are likely to support different communities, to flat areas, which may be sediment dominated (Clark et al. 2010). Seamounts in close proximity commonly share similar suites of species with each other and also with nearby areas of the continental margin (Hall-Spencer et al. 2007; McClain et al. 2009).

For this chapter, we use one of the most recent estimates of seamount number based on the work of Harris and colleagues (2014) (figure 17.1). These estimates not only align well with the IHO (2013) definition of seamounts but also include an estimate of the number of guyots as a separate class of seamount. Furthermore, this data includes additional information that helps define the geomorphic structure of seamounts—including area, height, slope, and depth of the summit—and can also be examined in the context of other geomorphic features defined by Harris and colleagues (2014).

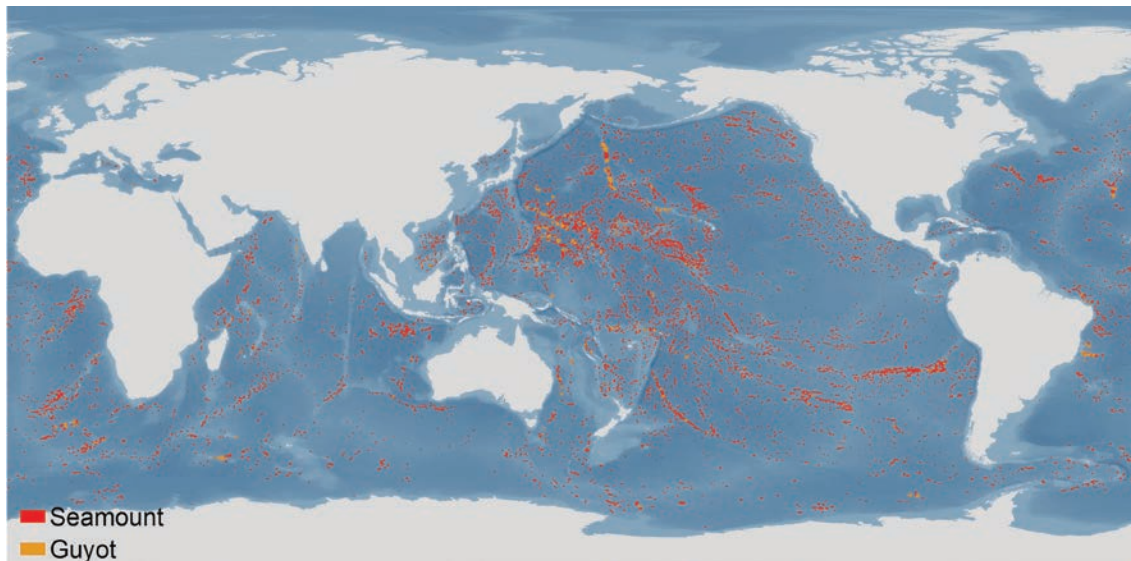


Figure 17.1. Global distribution of seamount and guyot features used in this analysis against the background of the Shuttle Radar Topography Mission 30 Plus version 11 bathymetric grid.

Global Seamount Distribution

Seamounts, although found in every major ocean region, are not evenly distributed across the globe (figure 17.2). The majority of seamounts, nearly 70%, are found in the North Pacific and South Pacific Ocean regions. These ocean regions also have the highest density of seamounts, with 49 and 35 seamounts, respectively, per million sq km compared with the global average of 28 seamounts per million sq km. These regions contrast sharply with the Arctic Ocean and the Mediterranean Sea, which have less than 0.5% of the global seamounts collectively and also the lowest density, at 1 and 8 seamounts per million sq km, respectively.

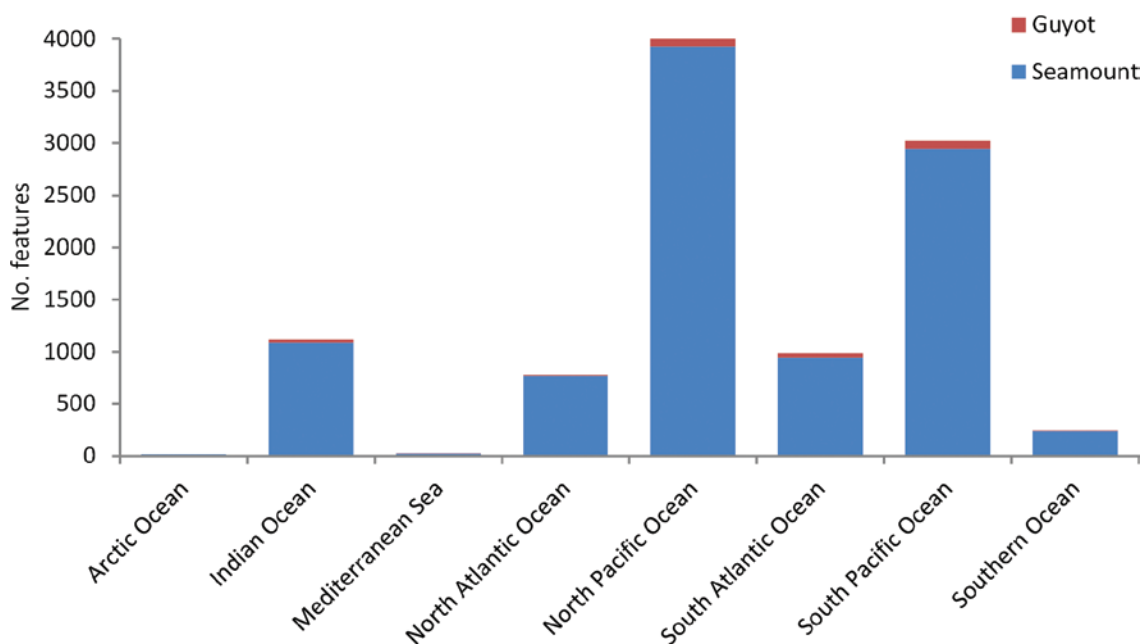


Figure 17.2. Global breakdown of seamounts and guyots by ocean region.

Seamounts occur relatively evenly within and outside national jurisdictions, with approximately 6,000 occurring in the high seas and 4,500 within national jurisdictions (figure 17.3). The density of seamounts is similar between the two areas, with around 29 seamounts per million sq km. Within national jurisdictions, there is a less even distribution of seamounts, with some countries being hot spots for seamounts and other countries having none within their jurisdictions. Not surprisingly, many of the countries with a large number of seamounts are within or adjacent to the North Pacific and South Pacific Ocean regions.

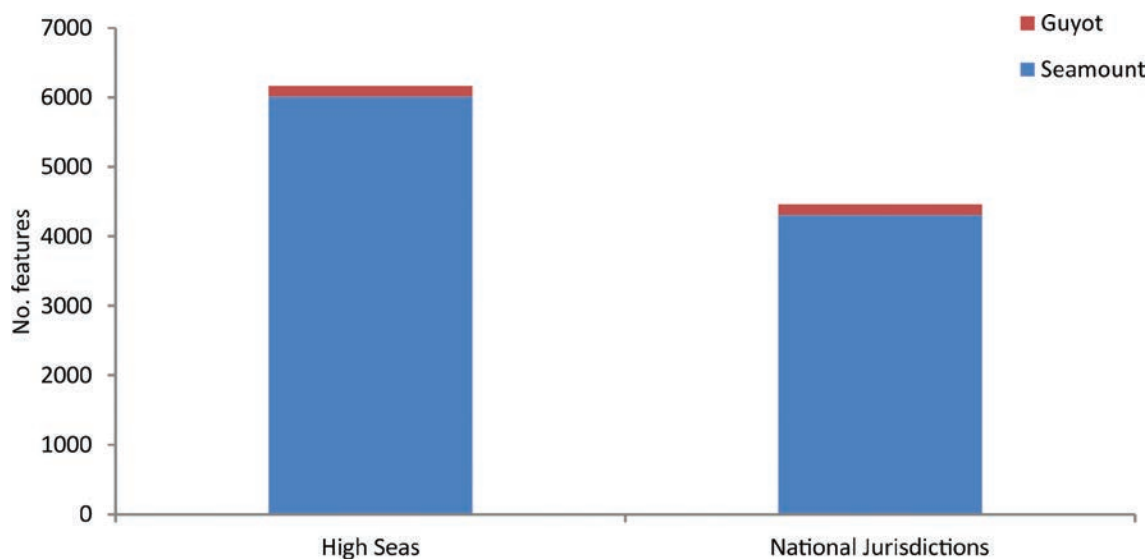


Figure 17.3. Seamounts and guyots within national jurisdictions and the high seas.

In terms of absolute numbers, French Polynesia has the highest number of seamounts within its national jurisdiction, with 322 identified seamounts (including five guyots). Other countries that have large numbers of seamounts within their jurisdictions include Japan, the United States (the majority around Hawaii), Kiribati, Marshall Islands, Mexico, Cook Islands, Federated States of Micronesia, Northern Mariana Islands and Guam, and Brazil. The highest density of seamounts occurs within the jurisdictions of Johnston Atoll and Palmyra Atoll (both unincorporated US territories), with 173 seamounts per million sq km. The contested Spratly Islands and Parcel Island in the South China Sea also have high densities of seamounts, at 141 and 116 per million sq km, respectively. The remaining countries with the highest density of seamounts are all Pacific Island countries.

All the preceding countries and territories with high numbers and densities of seamounts occur within an area known as the Pacific Ring of Fire, an area around the rim of the Pacific Ocean basin with a large number of earthquakes and volcanoes related to plate tectonics. Many of these areas of high seamount density may be, in part, a reflection of the amount of ship tracking data contributing to the SRTM bathymetric model, with many of the areas identified having high concentrations of ship tracks (Becker et al. 2009).

Many of the Pacific Island countries within the Ring of Fire, in which seamount numbers are highest, have limited resources to manage the multiple uses of the marine environment. This lack of resources extends to managing the activities and resources associated with seamounts. For this reason, it is important to prioritize seamounts for management on the basis of likely associated threats and demands for resources that countries must address. Several attempts have been made to create classification schemes for seamounts to help prioritize management. For example, Clark et al. (2011) developed a global seamount classification to assist in marine protected area planning.

These workers identified 194 seamount classes based on four biologically relevant variables, including overlying export production, summit depth, oxygen levels, and seamount proximity.

This chapter presents a multivariate method for classifying seamounts in types based on their physical characteristics. The resulting seamount types are examined in the context of their distribution within ocean regions, marine jurisdictions, and global bioregions. The role of such a classification in developing management priorities is discussed using the Clarion-Clipperton Zone, managed by the International Seabed Authority, and Kiribati's national jurisdiction (a developing country with a high density of seamounts) as examples.

Methods

Multivariate Analysis

The data preparation and spatial analysis were carried out using the tools incorporated in ArcGIS 10.3. The statistical analysis was carried out using the R statistical package. The seamount datasets were extracted from the global seafloor geomorphic features map accessed from www.bluehabitats.org (Harris et al. 2014) (figure 17.1). For the purpose of this analysis, both seamounts and guyots were combined into a single vector layer and are hereafter referred to as *seamount features*.

The seamount features data developed by Harris and colleagues (2014) was based on version 7 of the SRTM30 Plus bathymetry grid (Becker et al. 2009), and the seamount features were checked against the latest version (version 11, or v11) and the statistics recalculated. Seamounts that no longer fulfilled the criteria of a minimum height of 1,000 m were removed from the analysis. In total, 9,920 seamount features were included in this analysis. New seamount features were not interpreted from the updated SRTM30 Plus v11 bathymetry grid as part of this study.

For each seamount feature, five morphometric parameters were calculated on the basis of feature morphology and proximity using ArcGIS 10.3, as described here. The five morphometric parameters are the basal area, height, peak depth, proximity, and percentage area of escarpment (table 17.1). Basal area was calculated using the Calculate Geometry tool and represented the seamount feature footprint. Height of each seamount feature was calculated on the basis of the difference between the minimum depth and maximum depth of each feature. Minimum and maximum depths were calculated using the Zonal Statistics as Table tool, with the seamount features set as the input zones and the SRTM30 Plus v11 as the input value raster. Peak depth of each seamount was taken as the minimum depth from the preceding zonal statistics analysis. Percentage escarpment was calculated as the proportion of area with a slope of greater than 5 degrees. To calculate this value, the SRTM Plus v11 grid was reclassified into two classes, less than 5 degrees and greater than 5 degrees. The area of each seamount feature belonging to the greater-than-5-degree class was calculated and used to determine the percentage of escarpment on the seamount. The final parameter was the proximity of each seamount feature to other such features or the shelf break. The proximity analysis Near tool was used in a two-stage process. The first stage calculated the geodesic distance to the nearest seamount feature, while the second stage calculated the geodesic distance to the shelf break, as defined by Harris and colleagues (2014). The proximity metric was the smaller of these two numbers.

Table 17.1. Definition of the Five Morphometric Parameters Used in the Analysis of Global Seamount Features

Parameter	Description
Basal area	The planar area of the seamount polygon
Height	The height of the seamount (maximum depth minus minimum depth) based on the SRTM30 v11 bathymetric model
Peak depth	The minimum depth of the seamount based on the SRTM30 v11 bathymetric model
Percentage escarpment	The proportion of each seamount feature with slope greater than 5 degrees based on the SRTM30 v11 bathymetric model
Proximity	The distance to the nearest seamount or the shelf break based on geodesic distance

The data for the five morphometric parameters was used to classify the 9,920 seamount features into morphotypes using an approach similar to that used to develop global seascapes (Harris and Whiteway 2009). The statistical analysis was conducted using the R statistical package. Prior to analysis, the five morphometric parameters were examined for correlation using pairwise biplots. There was no strong correlation between any of the morphometric parameters (max $R^2 = 0.34$). Because of the different ranges and magnitudes of the five morphometric parameters, the data was scaled using the scale function to ensure equal weighting in the classification process. No additional weightings were given to any of the five morphometric parameters in the analysis.

A multivariate approach was chosen for the classification of morphometric data, as this type of approach is largely objective and allows natural groupings in the data to be identified (Rowden et al. 2005; Clark et al. 2011). Multivariate approaches work best using continuous variables, such as the five morphometric parameters used here. An alternative would be to use a predefined hierarchical framework to classify each of the parameters into classes, and then use these as the basis for identifying seamount morphotypes (Clark et al. 2011). This type of subjective approach is useful when the relationships between the variables and underlying biodiversity are well known. However, in this case, although the parameters are known to relate to biodiversity, the exact nature of these relationships and thus the thresholds for the classification are not well known.

The k-means algorithm was used to partition the data into a small number of clusters, with each observation—in this case, seamount feature—belonging to the cluster with the nearest mean. The first step in k -means clustering is to determine the number of clusters in the data. Two methods were employed to determine the number of clusters: the first based on a comparison of the within groups sum of squares for different numbers of clusters, and the second a comparison of the F -ratio for different numbers of clusters. The first method involved calculating the within groups sum of squares for between 2 and 20 clusters. This data was plotted, with a sharp change in the slope of the curve indicating a good number of clusters. The within groups sum of squares plot resulted in a gradual curve, with the largest relative changes between 4 and 12 clusters suggesting that the most effective number of clusters was in this range (figure 17.4).

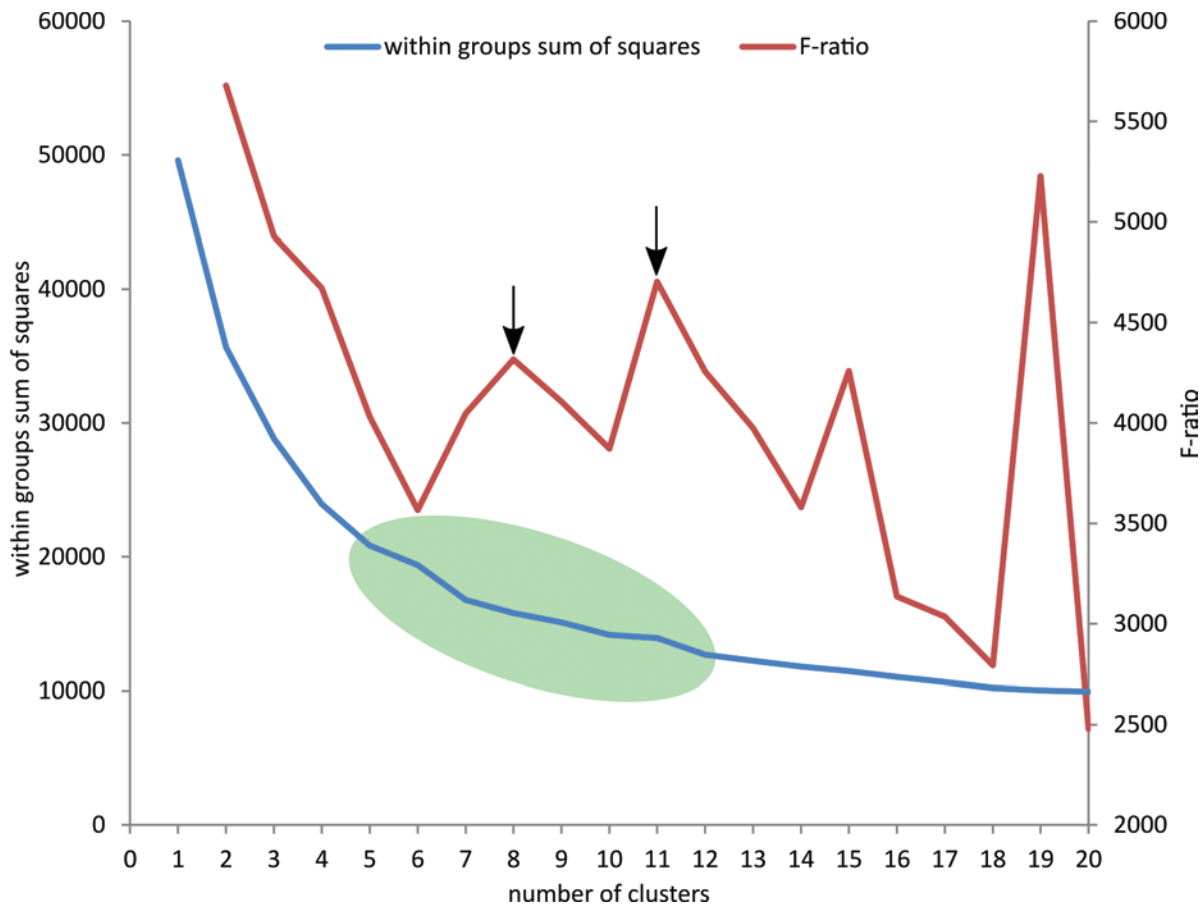


Figure 17.4. Plot of the within groups sum of squares and F -ratio against the number of clusters (2–20) based on k -means clustering results. The green zone on the within groups sum of squares curve highlights the region of gradual decrease of the within groups sum of squares. The two black arrows indicate local maxima in the F -statistic, which represents the optimal number of clusters.

The second method used the F -ratio, which reflects within-group similarity and between-group differences. The largest F -ratio was taken to represent the most effective number of clusters. When plotted against the number of clusters, several distinct peaks in the F -ratio were observed. Two of these peaks occurred in the region between 4 and 12 clusters indicated by the within groups sum of squares method, at 8 clusters and 11 clusters (figure 17.4). The 11-cluster peak was the larger of the two, so it was chosen as the number of clusters for the subsequent k -means clustering. The 11 clusters are each considered a separate type of seamount, or *morphotype*.

Hierarchical clustering was used to explore the relationship between the 11 morphotypes identified in the cluster analysis. A distance matrix (`dist(as.matrix(data))`) was created in R on the basis of the mean values of the five variables for the 11 clusters. Hierarchical clustering (`hclust`) was then used to plot a dendrogram of the relationship between the 11 morphotypes.

Principal component analysis was conducted on each of the 11 morphotypes to identify which of the five morphometric parameters was most responsible for each of the morphotypes. The `princomp` function was used to calculate the principal components based on the covariance matrix. The first two principal components were plotted using a biplot to show which variables contribute to variance in the data.

Assessment of Seamounts within Oceans and Marine Jurisdictions

The distribution of these 11 clusters was examined in relation to the global ocean regions (as defined in Harris et al. 2014) and marine jurisdictions to gain some understanding of the relative distribution of the different seamount types. Seamounts were attributed to one of the eight ocean regions (including the Mediterranean Sea) according to the location of their centroid, so that a seamount feature that straddled two ocean regions was attributed to only the single ocean in which its centroid was located. This information was used to collate statistics on the number and proportion of each seamount type within each ocean region.

Similarly, the distribution of 11 seamount types within national jurisdictions and the high seas was determined on the basis of their intersection with the maritime boundaries geodatabase (Flanders Marine Institute 2005). Again, the position of the seamount centroids was used to determine to which jurisdiction to attribute the seamounts. As for the oceans, this information was used to collate statistics on the number and proportion of each seamount type within each ocean region.

Within the high seas area, the representation of seamount types within the Clarion-Clipperton Zone, managed by the International Seabed Authority (ISA), was examined. This area is actively managed for marine mineral exploration, and so the seamounts within this region may be impacted by such activities.

The final part of the analysis extracted a subset of seamounts from Kiribati's marine jurisdiction, based on the maritime boundaries geodatabase, and examined these seamounts in the context of the Global Open Oceans and Deep Seabed (GOODS) habitat bioregions (Watling et al. 2013). In all cases, the number of each seamount type within each reporting region (i.e., ocean region, jurisdiction, or bioregion) was collated into a Microsoft Excel table and basic statistics on the number and proportion of each feature calculated and compared.

Results

Description of the 11 Seamount Morphotypes

The 11-cluster analysis identified 11 different seamount morphotypes, which can be described by differences in the five input variables (table 17.2). Hierarchical clustering showed that these 11 seamount morphotypes can be described under five broad groupings: (1) very large and tall with low escarpment, (2) large and tall with shallow peak, (3) intermediate, (4) small with deep peak, and (5) small and short with very deep peak (figure 17.5). A description of each of the 11 seamount morphotypes follows, using these five groupings.

Table 17.2. Mean Values of the Five Morphometric Parameters for the 11 Seamount Morphotype Features

Morphotype	No. features	Area (sq km)	Height (m)	Peak depth (m)	Proximity (km)	Escarpment (%)
1	1207	524	1536	2102	46	55
2	1745	496	2027	2781	39	81
3	1189	727	3148	1569	46	89
4	555	605	1700	2909	211	57
5	979	519	2114	1043	35	78
6	57	8788	4611	915	61	39
7	947	749	1410	3289	67	33
8	1298	480	1549	3744	49	63
9	262	3743	4217	767	46	54
10	816	1692	4115	672	36	70
11	865	1471	2855	1823	50	58

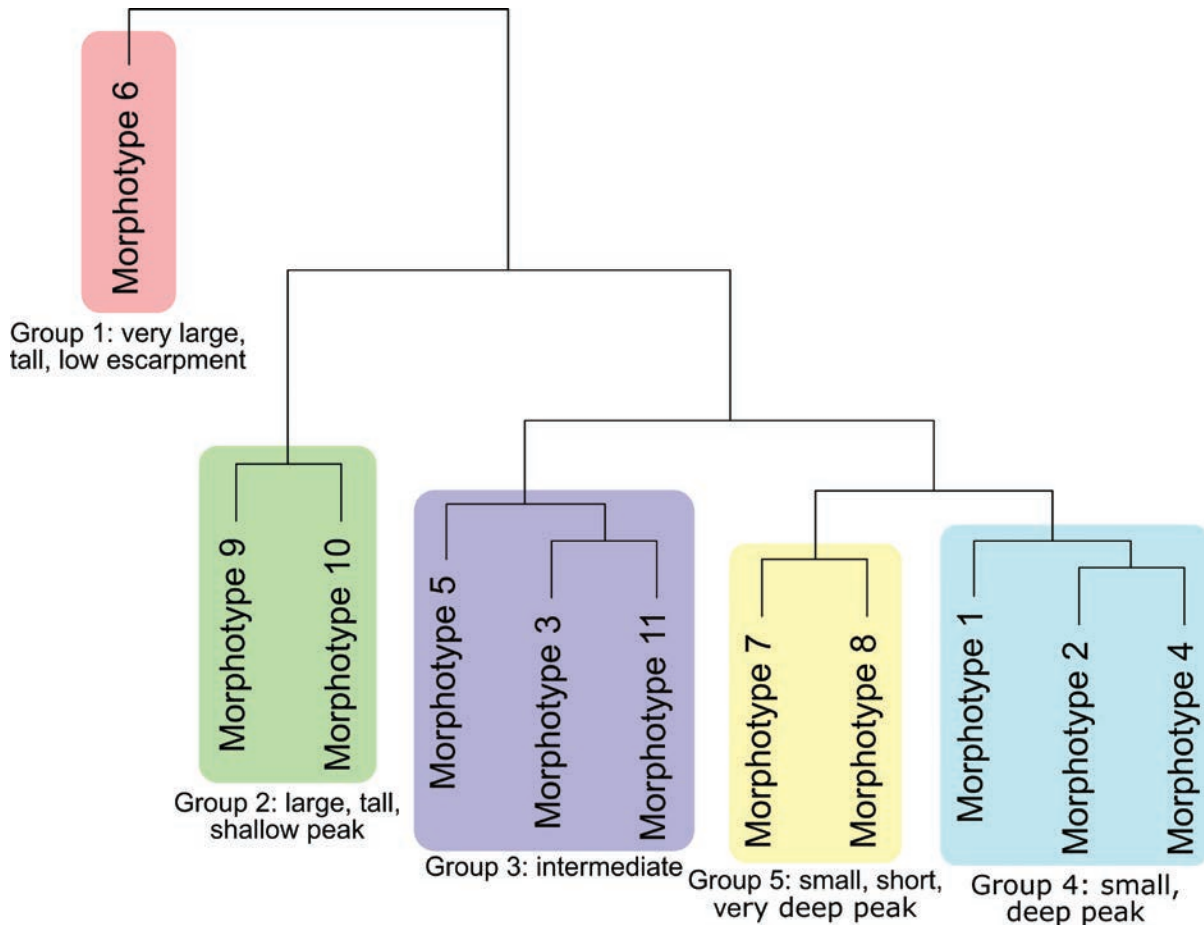


Figure 17.5. Dendrogram based on hierarchical clustering showing the relationship between the 11 seamount morphotypes. The morphotypes are grouped into five broad types based on similarities in one or more of the five parameters.

Group 1: Very Large and Tall with Low Escarpment

Seamount morphotype 6 seamounts are the only member of this group (figure 17.5), with seamounts characterized as very large and tall with generally shallow peak depths and a low amount of escarpment (table 17.2, figure 17.6). Principal component analysis indicated that the first two principal components explain over 90% of the variance. These principal components correlate with area ($R = 0.99$), proximity ($R = 0.65$), and height ($R = 0.54$). This morphotype included a high proportion of guyots (65%), which may account for the lower proportion of escarpment because of the proportionally large summit plateaus. Around 75% of morphotype 6 seamounts are found in the North Pacific Ocean.

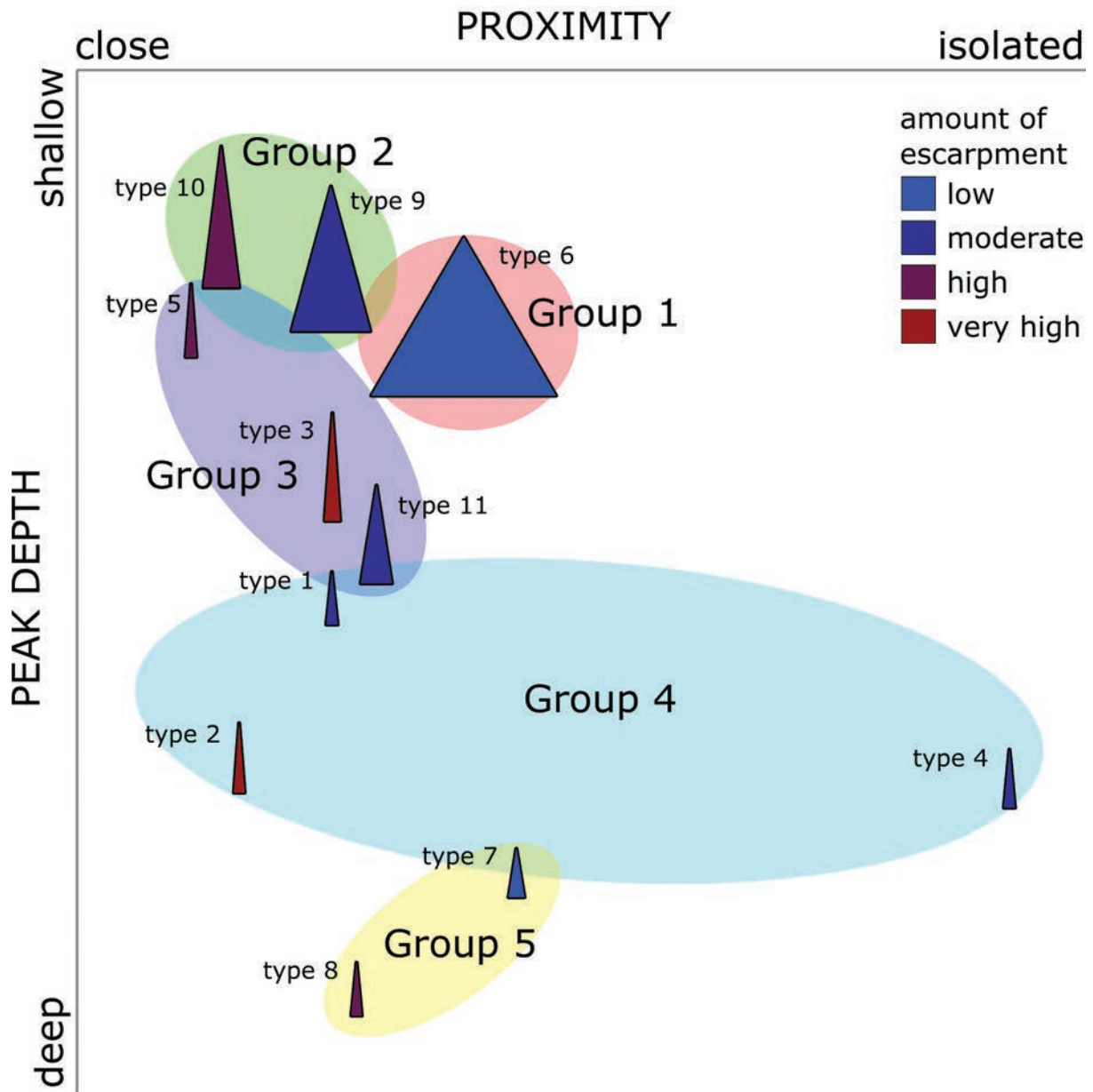


Figure 17.6. Schematic of the 11 seamount morphotypes and the five groups. The position along the vertical axis represents the mean peak depth from shallow to deep; the position along the horizontal axis represents the mean proximity to other seamounts from close to isolated; the height of the icon represents the mean height; the width of the icon represents the mean area; and the color of the icon represents the amount of escarpment.

Group 2: Large and Tall with Shallow Peak

This group contained two morphotypes, morphotypes 9 and 10 (see figure 17.5). These two morphotypes are characterized as large and tall with shallow peak depths (see table 17.2, figure 17.6). Morphotype 9 seamounts typically have a larger basal area and a smaller amount of escarpment compared with morphotype 10 (see table 17.2, figure 17.6). Morphotype 9 seamounts have the second-largest area and height of all the morphotypes. This morphotype has the second-shallowest peak depth. Principal component analysis indicated that the first two principal components explain 61% of the variance. These principal components correlate with area ($R = 0.81$), height ($R = 0.53$) and escarpment ($R = -0.52$). A large proportion of this morphotype are characterized as guyots, with over 31% of morphotype 9 seamounts classified as guyots by Harris and colleagues (2014). Morphotype 9 seamounts are most numerous in the North Pacific and South Pacific Ocean, with 71% of this morphotype occurring in these two ocean basins. This morphotype is not present in the Arctic Ocean or Mediterranean Sea.

Morphotype 10 seamounts are characterized by having the shallowest peak depth of all morphotypes (see table 17.2, figure 17.6). Morphotype 10 seamounts are also found in close proximity to other seamounts or the shelf break, with an average proximity of 36 km. Principal component analysis indicated that the first two principal components only explain 54% of the variance. These principal components correlate with height ($R = 0.86$), area ($R = -0.66$), and escarpment ($R = 0.66$). Approximately 10% of morphotype 10 seamounts are classified as guyots by Harris and colleagues (2014). Morphotype 10 seamounts are the most numerous in the North Pacific and South Pacific Ocean; however, it is also numerous in the North Atlantic Ocean, where it comprised nearly 13% of all seamounts compared to 8% globally.

Group 3: Intermediate

The intermediate group contains three morphotypes: 5, 3, and 11 (see figure 17.5). The seamounts in this group are characterized as small to medium with medium heights and a gradation in peak depths from moderately shallow to moderately deep. The seamounts in this group generally have high amounts of escarpment, with the exception of morphotype 11 seamounts, which have moderate amounts of escarpment.

Morphotype 5 seamounts are characterized as small, moderately tall, and with the shallowest peak depths of the intermediate seamounts (see table 17.2, figure 17.6). Morphotype 5 exhibits the closest proximity of all seamount morphotypes, with an average distance of 35 km to the nearest seamount or to the nearest shelf break. Morphotype 5 seamounts are also characterized by a high percentage of escarpment. There are a small number of guyots within this morphotype; however, the majority of the features are classified as seamounts by Harris and colleagues (2014). Principal component analysis indicated that the first two principal components described 58% of the variance. These principal components correlate with peak depth ($R = 0.66$), escarpment ($R = -0.70$), and proximity ($R = -0.50$). Morphotype 5 seamounts are most commonly found within country jurisdictions, with over 60% of this morphotype occurring in national jurisdictions compared with the global average of 41% for all morphotypes combined. Morphotype 5 seamounts are proportionally most common in the Arctic Ocean and the Mediterranean Sea, where they comprise 33% and 44% of all seamounts, respectively.

Morphotype 3 seamounts are on average larger, taller, and with a deeper peak depth compared with morphotype 5 (see table 17.2, figure 17.6). Morphotype 3 seamounts also contain the greatest percentage area of escarpment of any of the morphotypes. Principal component analysis indicated that the first two principal components describe 61% of the variance. The first two principal

components correlate with peak depth ($R = -0.74$) and proximity ($R = 0.79$). Morphotype 3 seamounts occur within all ocean basins, with the exception of the Arctic Ocean.

Morphotype 11 seamounts are the largest in terms of area of the three morphotypes that make up this group. Morphotype 11 seamounts are characterized as having the deepest peak depth of these three morphotypes (see table 17.2, figure 17.6). Morphotype 11 has a low number of guyots. Principal component analysis indicated that the first two principal components describe 53% of the variance. The first two principal components correlate with peak depth ($R = -0.76$), escarpment ($R = -0.57$), and area ($R = -0.72$). Morphotype 11 seamounts occur within every ocean basin, generally comprising between 5% and 12% of all seamounts.

Group 4: Small with Deep Peak

The “small with deep peak” seamount group contains three seamount morphotypes: 1, 2, and 4 (see figure 17.5). These morphotypes are characterized as small, short, and with deep peak depths. This group of morphotypes is one of the more numerous, as it is found in all the ocean basins. These morphotypes are most abundant in the North Pacific and South Pacific Ocean.

Morphotype 1 seamounts are small, short seamounts with moderately deep peak depths (see table 17.2, figure 17.6). Morphotype 1 seamounts have the second-smallest area (524 km²) and the second-smallest height (1,536 m). Principal component analysis indicated that the first two principal components describe 62% of the variance. The first two principal components correlate with escarpment ($R = -0.74$), proximity ($R = 0.91$), and peak depth ($R = -0.59$). Morphotype 1 seamounts are found in all the ocean basins; and although the highest numbers are in the North Pacific and South Pacific Ocean, the southern ocean also has a proportionally high number of morphotype 1 seamounts comprising 22% of all seamounts in this ocean basin.

Morphotype 2 seamounts are the second-smallest morphotype (496 km²), with deep peak depth and moderate height (see table 17.2, figure 17.6). Morphotype 2 seamounts have the highest amount of escarpment (81%) and second-closest proximity (39 km). Morphotype 2 is the most common seamount morphotype, with 1,745 seamounts identified as this morphotype. Principal component analysis indicated that the first two principal components describe 54% of the variance. The first two principal components correlate with height ($R = -0.65$) and proximity ($R = -0.81$). Morphotype 2 seamounts are found in all ocean basins.

Morphotype 4 seamounts are the final morphotype in the small with deep peak group. Morphotype 4 seamounts are the most isolated morphotype with an average proximity of 211 km (see table 17.2, figure 17.6). This morphotype is found predominantly outside national jurisdictions, with 84% found in areas beyond national jurisdiction. Principal component analysis indicated that the first two principal components describe 85% of the variance. The first two principal components correlate with proximity ($R = 0.99$) and escarpment ($R = 0.85$). Morphotype 4 seamounts are found in all ocean basins except the Mediterranean Sea. They are most common in the Indian and South Pacific Oceans.

Group 5: Small and Short with Very Deep Peak

Two morphotypes are present in the “small and short with very deep peak depth” seamount group: morphotypes 7 and 8 (see figure 17.5). Morphotype 7 seamounts are the second-most isolated, with an average proximity of 67 km. They also have the lowest proportion of escarpment (33%) and are the shortest (1,410 m; see table 17.2, figure 17.6). Principal component analysis indicated that the first two principal components describe 60% of the variance. The first two principal components correlate

with proximity ($R = -0.97$) and peak depth ($R = 0.86$). Morphotype 7 seamounts are found in all ocean basins, with the exception of the Arctic Ocean and the Mediterranean Sea. They are most common in the North Pacific and South Pacific Ocean.

Morphotype 8 seamounts are the smallest seamounts in terms of mean area (480 km^2), and they have the deepest peak depth (3,744 m) (see table 17.2, figure 17.6). Principal component analysis indicated that the first two principal components describe 62% of the variance. The first two principal components correlate with proximity ($R = 0.98$) and escarpment ($R = 0.87$). Morphotype 8 seamounts are proportionally the second-most common in areas beyond national jurisdiction (70%). They are found in all ocean basins, with the exception of the Arctic Ocean and the Mediterranean Sea.

Distribution of Seamount Types by Ocean Basins

The distribution of each of the 11 seamount morphotypes is not uniform among the major ocean basins (figures 17.7 and 17.8). The greatest densities of seamounts occur within the North Pacific and South Pacific Ocean, with 48 and 34 seamounts per million sq km, respectively. The Arctic Ocean has the lowest density of seamounts, with only 1 seamount per million sq km, compared with a global average of 27 seamounts per million sq km.

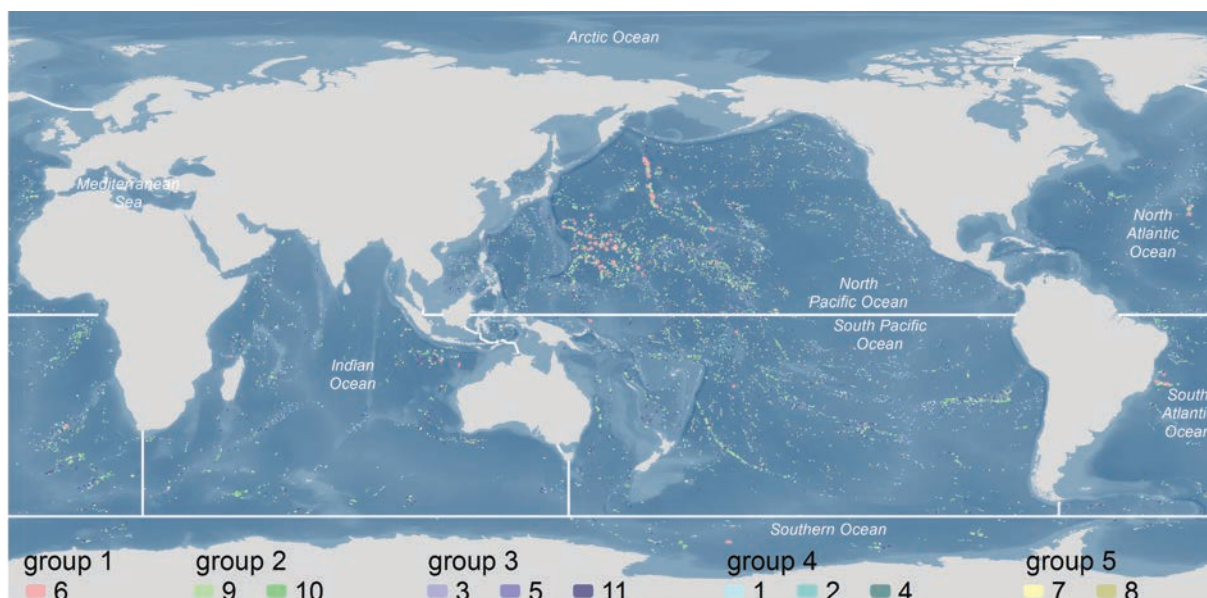


Figure 17.7. Distribution of 11 seamount morphotypes in relation to the global ocean basins.

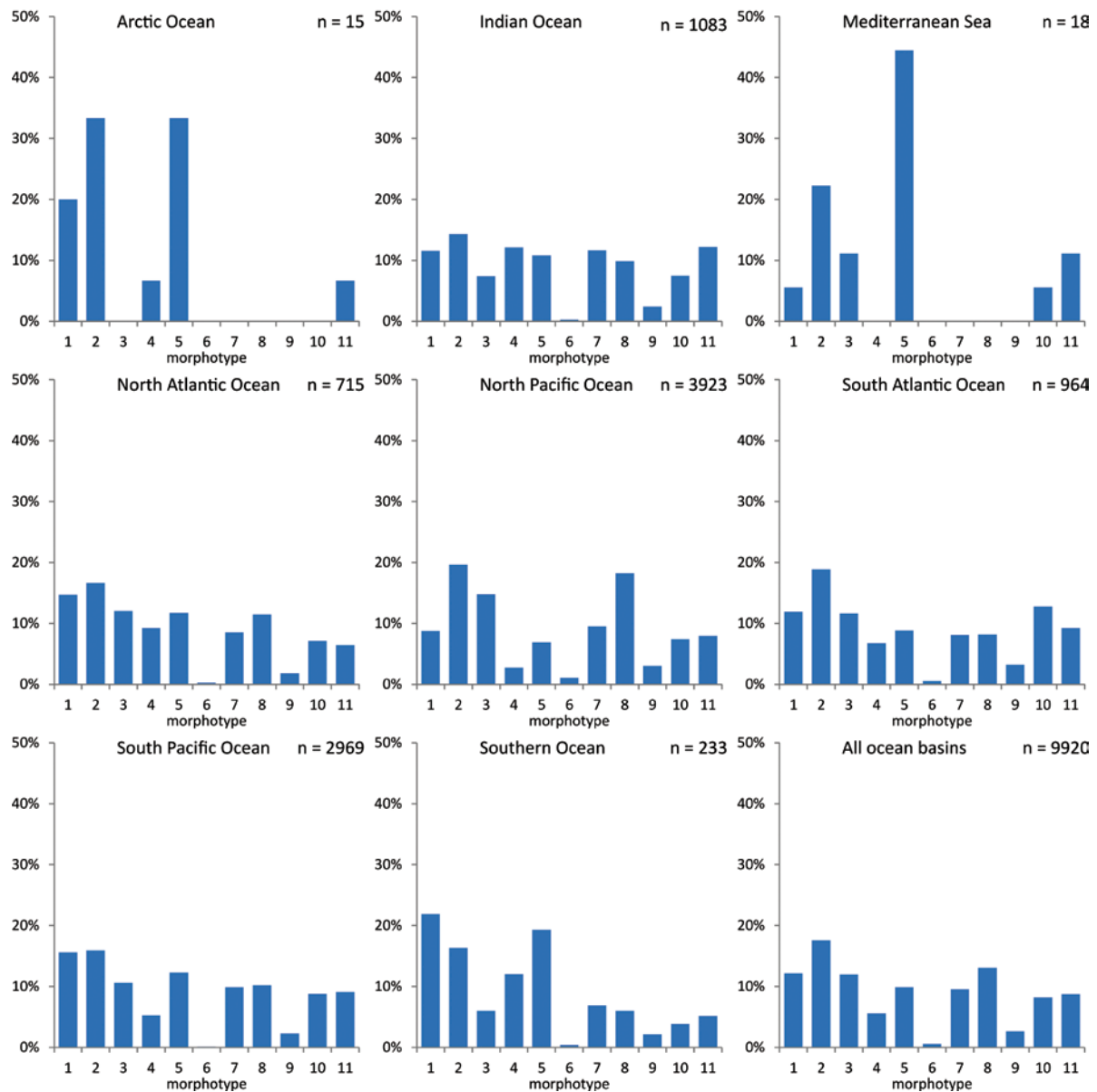


Figure 17.8. Proportion of the 11 seamount morphotypes by ocean basin and global average. The vertical axis represents the proportion of a seamount type by ocean region.

Each of the ocean basins has representatives of the 11 seamount morphotypes, with the exception of the Arctic Ocean and the Mediterranean Sea. The Arctic Ocean has only 5 of the 11 seamount morphotypes represented, while the Mediterranean Sea has only 6 of the 11 morphotypes present (see figure 17.8). These two ocean basins have the lowest number of seamounts overall (15 and 18 seamounts, respectively), which accounts for the low number of morphotypes found. Within the other ocean basins, the seamount morphotypes are proportioned differently.

Group 1 seamounts (morphotype 6) are either not present or present in very low numbers in most ocean basins. These very large seamounts and guyots are most common in the North Pacific Ocean, where over 75% of these features are found. Group 2 seamounts (morphotypes 9 and 10) are present in all ocean basins, except the Arctic Ocean and the Mediterranean Sea. Morphotype 9 seamounts are present in larger numbers in the North Pacific, South Pacific, South Atlantic, and Indian Oceans. Proportionately, morphotype 9 seamounts are best represented in the North Pacific and South

Atlantic Oceans, making up around 3% of all seamounts. Morphotype 10 shows a similar pattern to morphotype 9, with the South Atlantic Ocean having the greatest proportion of morphotype 10, making up 13% of all its seamounts. Based on these observations, it appears that the North Pacific has a high proportion of large and very large seamounts (groups 1 and 2) compared with other ocean basins.

Group 3 seamounts (morphotypes 3, 5, and 11) are present in all ocean basins, with the exception of morphotype 3, which is not present in the Arctic Ocean. Morphotype 3 is most common in the North Pacific Ocean, comprising 15% of all seamounts, and is also common in the North Atlantic and South Atlantic Ocean. Morphotype 5 is abundant in the North Pacific, South Pacific, and Indian Oceans; however, proportionately, it is best represented in the Arctic Ocean and Mediterranean Sea. Morphotype 11 is present in large numbers in the North Pacific, South Pacific, and Indian Oceans and is proportionately common in the Mediterranean Sea and Indian Ocean.

Group 4 seamounts (morphotypes 1, 2, and 4) are present in all ocean basins, with the exception of morphotype 4, which is not present in the Mediterranean Sea. Morphotype 1 is present in large numbers in most ocean basins, with particularly high numbers in the North Pacific and South Pacific Ocean. Proportionately, this morphotype is most common in the southern and Arctic Oceans, with over 20% of all seamounts in these ocean basins classified as morphotype 1. However, in the case of the Arctic Ocean, morphotype 1 accounts for only three seamounts. Morphotype 2 is the most common seamount morphotype and is found in all ocean basins in reasonably high proportions, with the Arctic Ocean having the highest proportion of this morphotype. Morphotype 4 is present in high numbers in the Indian, North Pacific, and South Pacific Oceans; it is proportionally the most common in the Indian and southern oceans.

Group 5 seamounts (morphotypes 7 and 8) are not present in the Arctic Ocean or in the Mediterranean Sea. Morphotype 7 is most common in the Indian, North Pacific, and South Pacific Oceans. Morphotype 8 is most common in the North Pacific Ocean.

Distribution of Seamount Types by Jurisdiction

A comparison of the proportion of each morphotype by national jurisdiction against those occurring in the areas beyond national jurisdictions (the high seas) shows that several morphotypes are more common in the high seas, while others are more common in national jurisdictions (figure 17.9). Morphotype 4 occurs mostly in the high seas, with approximately 3.5 times more of this morphotype. This morphotype is characterized as being the most isolated, with an average proximity to the nearest seamount or shelf break of 211 km, which is a similar scale to the width of most national jurisdictions.

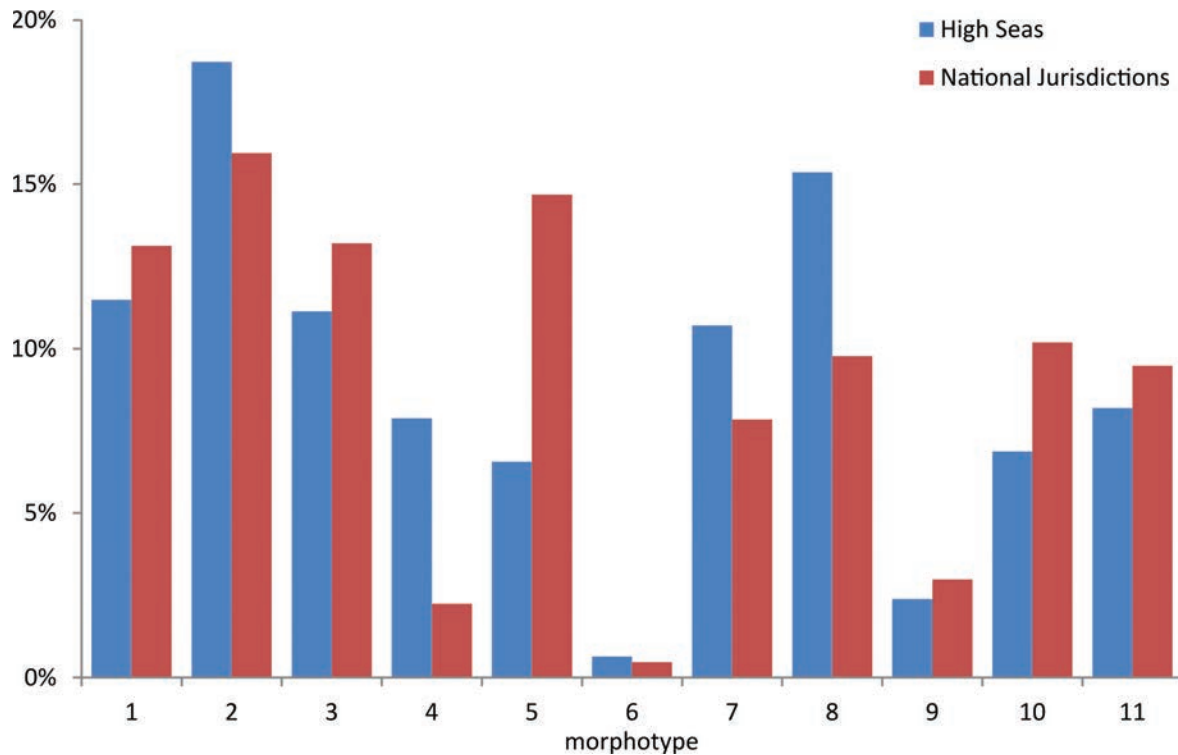


Figure 17.9. Percentage of the 11 seamount types within the high seas and national jurisdiction by morphotype.

Morphotypes 2, 7, and 8 are all proportionately more common in the high seas. Together with morphotype 4, these morphotypes have the deepest peak depths. These four morphotypes commonly occur in the deeper parts of the abyssal plain, the majority of which is located beyond national jurisdictions.

Morphotypes 1, 3, 5, 9, 10, and 11 are all more common in national jurisdictions than in the high seas area. Of these types, morphotype 5 is the most common in national jurisdictions, being twice as common in national jurisdictions as in the high seas area. This morphotype has the closest proximity to other seamounts, whereas the other morphotypes that are more common in national jurisdictions are characterized as having shallow peak depths and generally close proximity.

Seamount Types of the Clarion-Clipperton Zone

The Clarion-Clipperton Zone (CCZ) is an area of high seas in the northeast Pacific that is managed by the ISA for marine minerals exploration. A part of the management of Areas of Particular Environmental Interest (APEI) has been established to ensure the protection of a representative sample of ecosystems and biodiversity (figure 17.10). A total of 239 seamounts occur in the high seas areas of the CCZ. The distribution of seamount types within the CCZ and the APEI shows that 10 seamount morphotypes are present within the CCZ, with morphotype 6 not present.

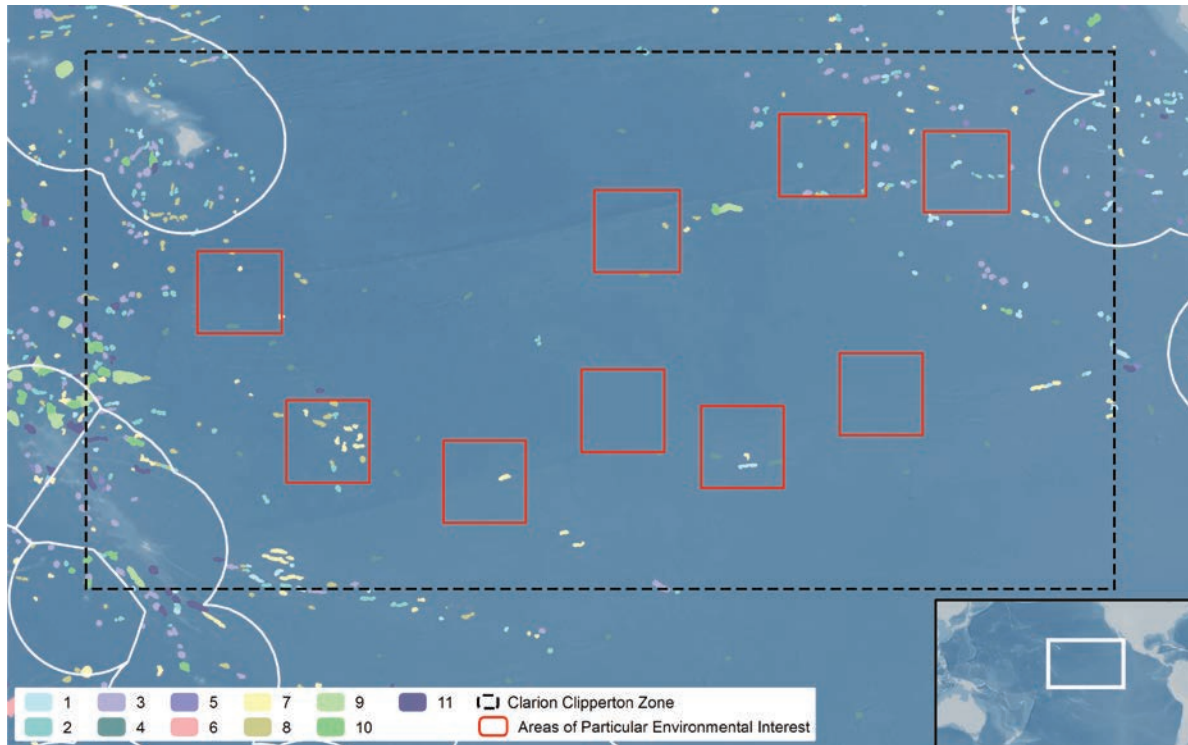


Figure 17.10. Distribution of the nine seamount types within the Clarion-Clipperton Zone and the Areas of Particular Environmental Interest.

Overall, 20% of all seamounts in the CCZ are represented within the APEI. When each seamount type is examined, morphotypes 7 and 8 are the best represented, with over 30% of each of these morphotypes incorporated into the APEI. Morphotypes 2 and 4 also have good representation in the APEI, with approximately 18% to 19% of these morphotypes within the APEI. These four morphotypes are all more common in areas beyond national jurisdiction; thus the APEI management regime of the CCZ contributes significantly to the global management of these seamount morphotypes. Although six seamount morphotypes have been incorporated within the APEI (figure 17.11), morphotypes 5, 9, 10, and 11 are not represented and thus would not be protected using the APEI scheme. Interestingly, these morphotypes are characterized as large with generally close proximity and shallow peak depths, and all are more common in national jurisdictions. The environmental management plan for this area aims for 30% to 50% of the management area to be protected and for the protected area to contain the full range of habitats and communities. Seamount morphotypes that are not represented or are poorly represented may become the focus of future management actions.

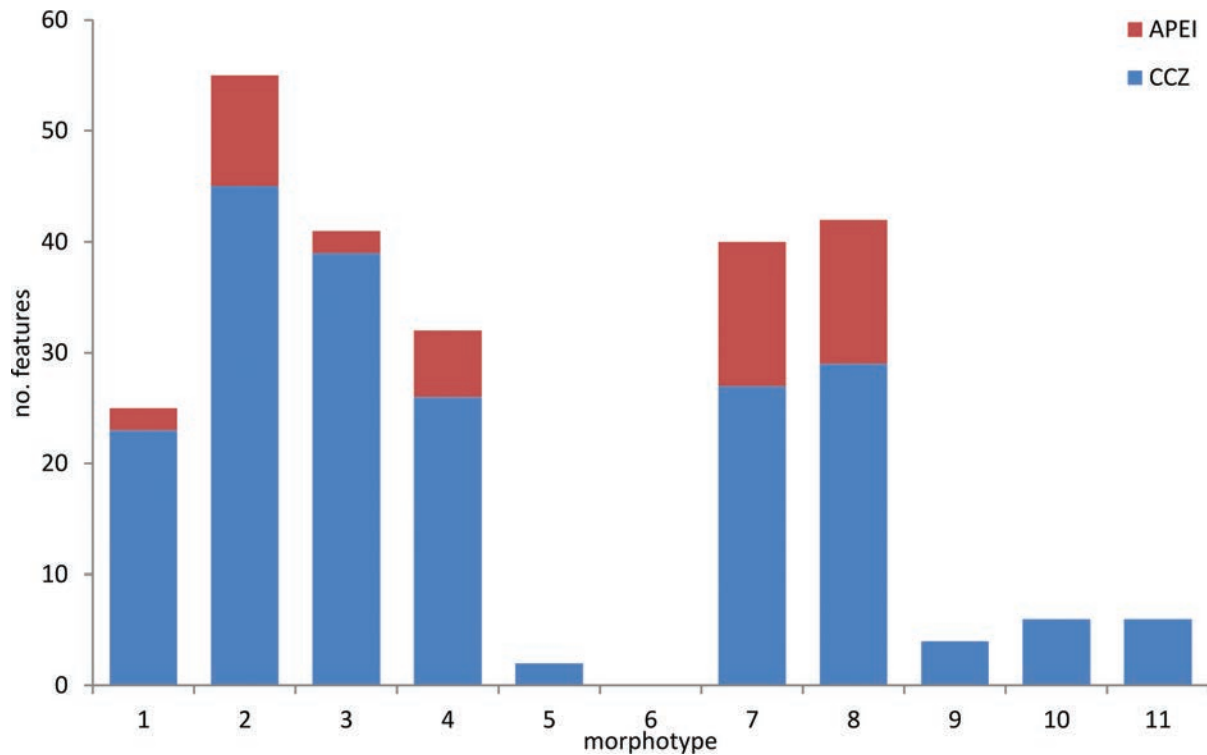


Figure 17.11. Summary of seamount types within the Clarion-Clipperton Zone (CCZ) and the Areas of Particular Environmental Interest (APEI).

Seamounts of Kiribati’s National Jurisdiction and the GOODS Bioregions

To undertake marine planning within a jurisdiction, information on the distribution and number of features (including seamounts) within that jurisdiction is required. Kiribati has 197 seamounts within its national jurisdiction. Ten of the 11 seamount morphotypes are represented within this area, with only morphotype 6 not present (figure 17.12). Morphotypes 2 and 3 are the most common morphotypes, with morphotypes 7, 8, 10, and 11 also common (figure 17.13). Morphotypes 1, 4, 5, and 9 are the least common seamount morphotypes, with between three and five of each of these morphotypes present. Compared with the global average of the different seamount morphotypes, Kiribati has proportionally fewer morphotype 1, 4, and 5 seamounts within its jurisdiction and proportionally more morphotype 3, 10, and 11 seamounts within its jurisdiction. This classification is important when identifying and prioritizing different seamounts for management actions.

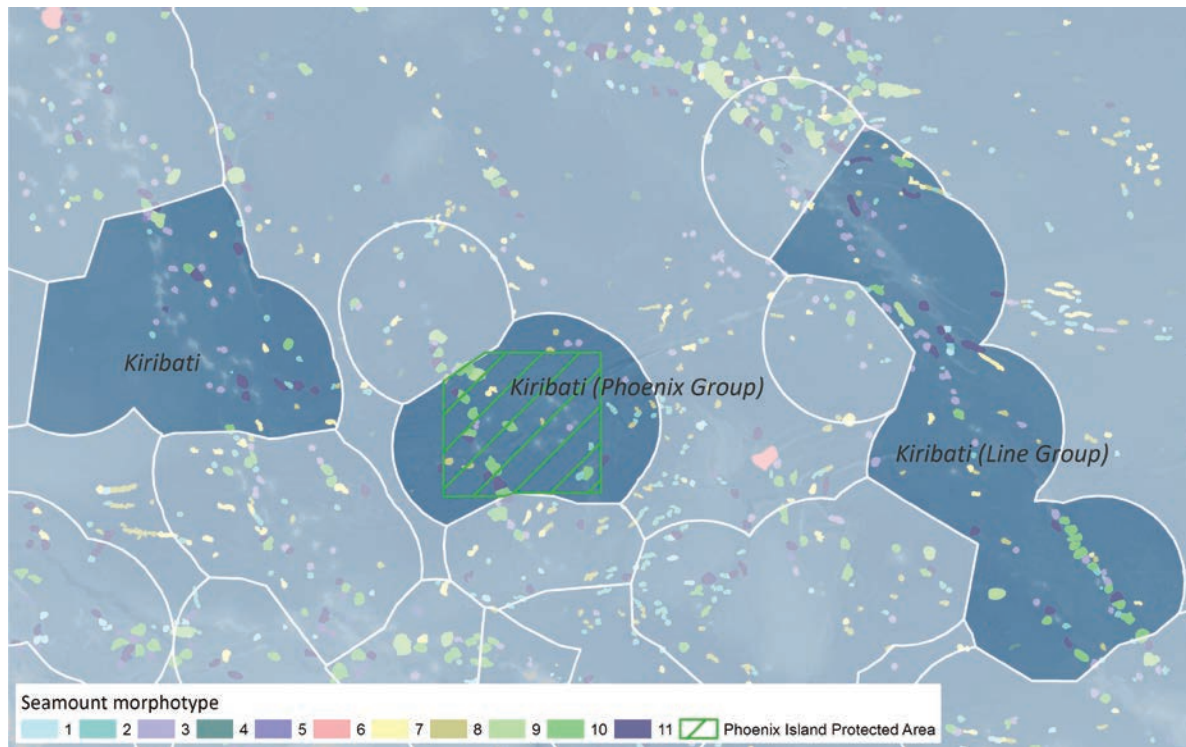


Figure 17.12. Distribution of the 11 seamount types within Kiribati's marine jurisdiction and location of the Phoenix Islands Protected Area.

Within Kiribati's national jurisdiction is a single large marine protected area, the Phoenix Island Protected Area (PIPA). The PIPA covers approximately 12% of Kiribati's national jurisdiction. Contained within the PIPA are 30 seamounts, which include 7 of the 10 morphotypes present within Kiribati's national jurisdiction. Morphotypes 9, 10, and 11 are all well represented in the PIPA, with between 23% and 35% represented (figure 17.13). The remaining morphotypes are represented at less than 7%. Thus the morphotypes that are currently underrepresented may become a priority in future marine planning.

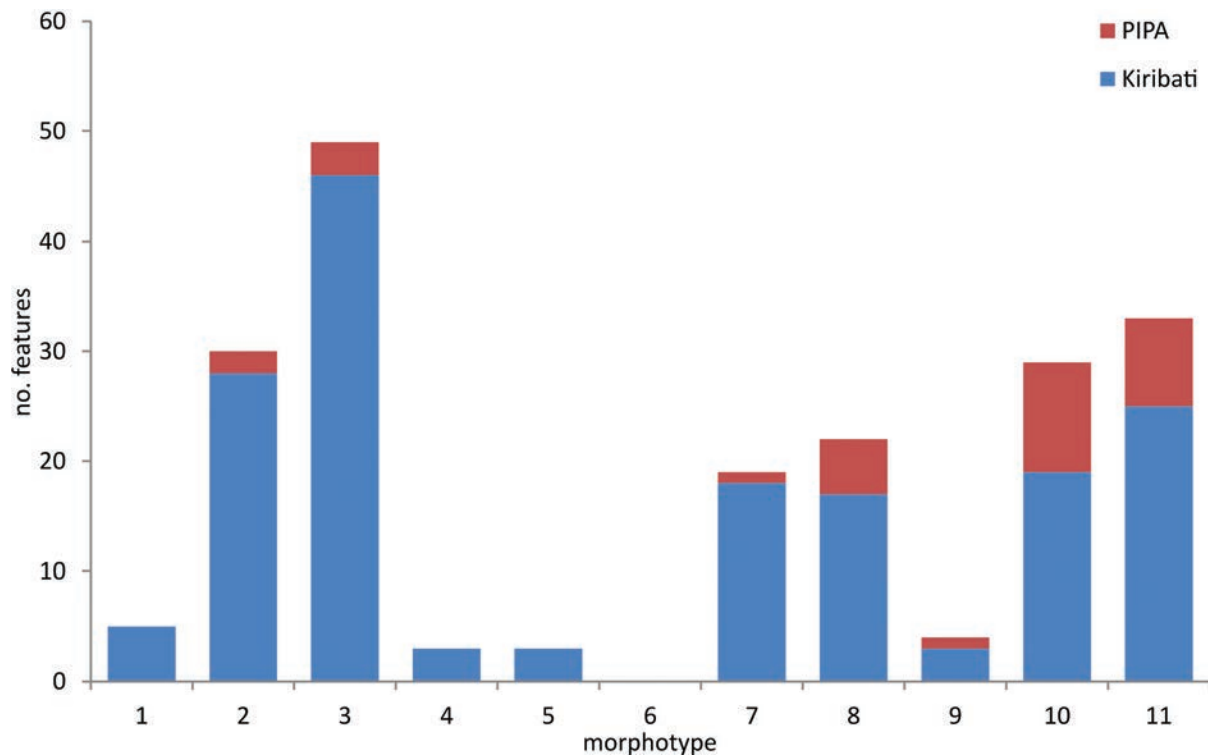


Figure 17.13. Breakdown of the 11 seamount types present within Kiribati’s national jurisdiction and within the Phoenix Island Protected Area (PIPA).

When examining the representation of seamount morphotypes it is important to consider the regional biogeography, because seamounts located within the same biogeographic zone are likely to support similar ecosystems and biodiversity. The GOODS biogeographic classification (Watling et al. 2013) is used as a basis to examine the representation of the seamounts within the Kiribati jurisdiction. Within Kiribati’s jurisdiction, four GOODS bioregions occur: the lower bathyal province 5 (Pacific), the abyssal provinces 10c and 10d (Pacific Ocean), and the Hadal Province. The seamounts within Kiribati’s marine jurisdiction occur within three of the four GOODS bioregions present, with none occurring within the Hadal Province. There are 49 seamounts within the lower bathyal province 5 and 128 seamounts within the abyssal province 10c. Only two seamounts occur within the abyssal province 10d. For this reason, only the seamounts that occur within the bathyal province 5 and abyssal province 10c are further examined.

The GOODS lower bathyal province 5 seamounts within Kiribati’s jurisdiction make up 14% of all known seamounts in this province. Ten of the 11 seamount morphotypes are present in the lower bathyal province 5, with morphotype 6 absent (figure 17.14). Within Kiribati’s marine jurisdiction, 8 of these 10 seamount morphotypes are present. Morphotype 5 is the most common morphotype within this GOODS bioregion, with 140 seamounts in this category; however, slightly over 2% of these seamounts are found only within Kiribati’s national jurisdiction. Proportionally, morphotypes 3, 9, 10, and 11 are the best represented within Kiribati’s marine jurisdiction, with between 25% and 44% of these seamount morphotypes from GOODS lower bathyal province 5 occurring within Kiribati’s national jurisdiction. These four morphotypes have shallow or moderately shallow peak depths, so fishing activities may impact them. Because of this effect, Kiribati has additional responsibility to ensure that these seamounts are well managed.

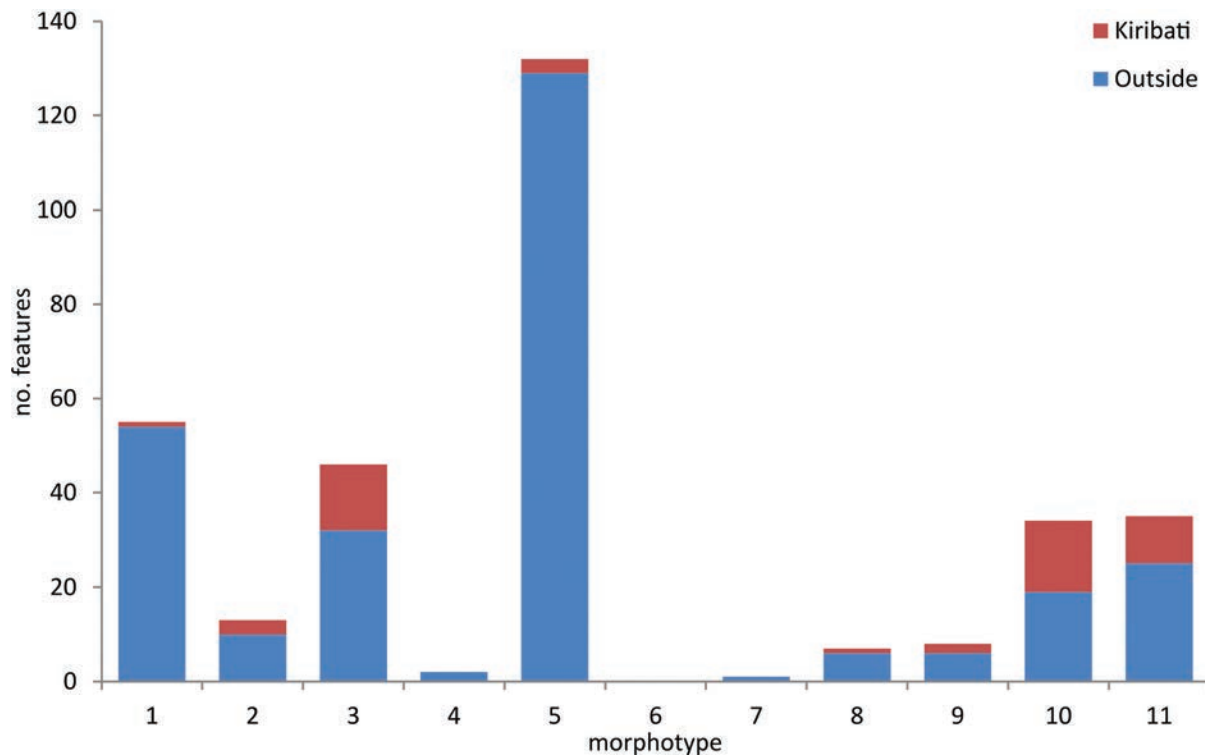


Figure 17.14. Seamount types within the Global Open Oceans and Deep Seabed lower bathyal province 5 (Pacific) and within Kiribati’s marine jurisdiction.

Within the GOODS abyssal province 10c, 10 of the 11 seamount morphotypes are present, with 9 of them also present within Kiribati’s marine jurisdiction. Morphotypes 3, 9, 10, and 11 are the most represented within Kiribati’s national jurisdiction, amounting to between 22% and 34% of these morphotypes (figure 17.15). Again, these morphotypes are all characterized by shallow to moderately shallow peak depths, especially morphotypes 9 and 10, and so may be more exposed to fishing pressure. Again, these morphotypes should be a priority for future management efforts.

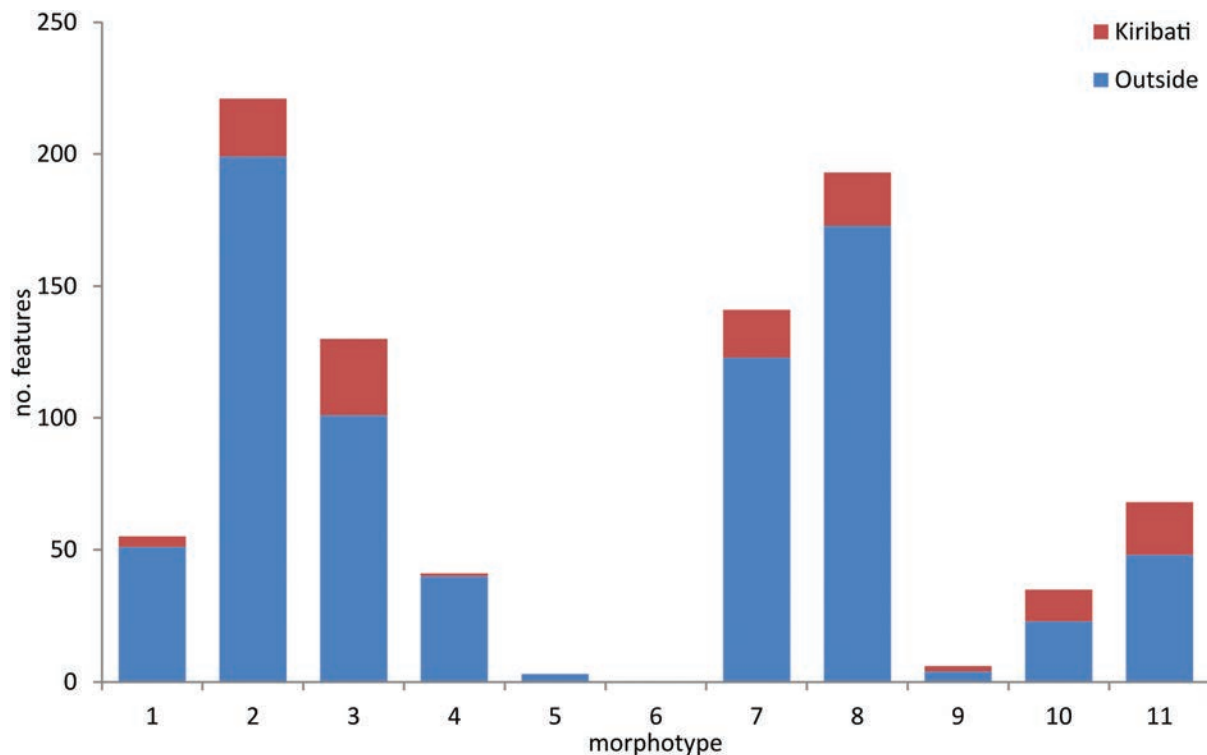


Figure 17.15. Seamount types within the Global Open Oceans and Deep Seabed abyssal province 10c (Pacific Ocean) and within Kiribati's marine jurisdiction.

Discussion and Conclusion

This chapter presents a multivariate classification of global seamounts based on their physical characteristics. Eleven different seamount types are identified based on differences in basal area, peak depth, height, proximity, and the amount of escarpment. The distribution of these different seamount types is then examined in relation to the global oceans, marine jurisdictions, and one available global bioregionalization, GOODS (Watling et al. 2013). Finally, the ways that this type of classification can help contribute to improved management is examined for the CCZ and within Kiribati's marine jurisdiction.

The multivariate cluster analysis was run for between 2 and 20 clusters. Eleven clusters are identified as an optimal number of clusters, with these clusters described by differences in morphometry. The most common seamount morphotype identified is morphotype 2, which accounts for approximately 18% of all seamounts. These seamounts are characterized as small, short, deep, closely spaced, and with a large amount of escarpment; and they are distributed globally. Other common types of seamounts include morphotypes 1, 3, and 8. All these morphotypes are generally small with deep peak depths and are moderately isolated.

The least common seamount morphotype is morphotype 6, with only 57 members, 65% of which are guyot features, as identified by Harris and colleagues (2014). Seamount morphotypes 9 and 10 also have a high proportion of guyot features (31% and 10%, respectively). These three morphotypes are characterized as large, tall, and with shallow peak depths. Morphotypes 5 and 11 include a number of guyot features, but they mostly consist of classic seamounts. That guyots did not fall out as a single morphotype is not surprising, considering that they (like all seamounts) exist in a range of shapes and sizes. Although all guyots share a common trait in having a plateau summit,

morphometrically they appear to be similar to many other seamounts based on the five morphometric parameters used in this study.

Physical variables have previously been shown to be useful in classifying seamounts. Rowden and colleagues (2005) found that 12 seamount types that they identified in New Zealand waters are largely characterized by just 4 of 13 environmental variables: depth at peak, depth at base, elevation, and distance from continental shelf. An unsupervised approach, such as the one described here, reflects statistical differences in the data to identify natural clusters and does not necessarily reflect gradients in the data that can be directly related to changes in biodiversity.

Although the 11 seamount morphotypes are not directly defined using biological data within this study, the physical variables that are used have some relationship to patterns of biodiversity. For example, steep rocky slopes on elevated peaks of seamounts that are exposed to strong currents support corals and other filter feeders (Genin et al. 1986). The combination of percentage area of escarpment and peak depth can help identify seamounts that may have a particular abundance of these types of habitats. Seamount morphotype 10, with its shallow peak depth and high proportion of escarpment, is more likely to support an abundance of suitable habitat for corals and other filter feeders. Similarly, seamount morphotypes 3 and 5 may also provide a significant amount of such habitat.

Soft sediments dominate some seamounts, particularly flat-topped guyots and banks (Clark et al. 2010). Many of the seamount morphotypes 6 and 9, with their shallow peak depths and high proportion of guyots, are likely to fall into this category. The fauna of this type of habitat has been shown to be similar to neighboring continental slopes (Gillet and Dauvin 2000; Ávila and Malaquias 2003). This similarity may have implications for the resilience of such habitats, with the location of these features in relation to the continental shelf and circulation patterns dictating the recruitment patterns between these similar habitats.

The application of the seamount classification described here to inform management was assessed using both the CCZ and Kiribati's marine jurisdiction as case studies. Within the high seas area of the CCZ, 239 seamounts are identified, with 10 of the 11 seamount types present. Only six of these seamount types are represented within the Areas of Particular Environmental Importance. The APEI has been established to protect a representative example of the habitats and ecosystems within the CCZ. According to the environmental management plan for this area, between 30% and 50% of the management area is to be protected, and the protected area should contain the full range of habitats and communities (Lodge et al. 2014; Seascope Consultants 2014). Based on analysis of the seamount types present within the CCZ, only morphotypes 8 and 9 are represented within the APEI at this level (33% and 31%, respectively). The remaining classes are represented at less than this target range, with morphotypes 5, 9, 10, and 11 not represented within the APEI. Interestingly, these four unrepresented seamount morphotypes are all characterized as medium to tall in height and with generally shallow peak depths.

Kiribati has similarly adopted spatial management measures for the protection of marine biodiversity in the form of the Phoenix Islands Protected Area. The PIPA is one of the largest marine protected areas in the world and covers approximately 12% of Kiribati's marine jurisdiction. Despite the PIPA's large size, not all the seamount morphotypes present within Kiribati's marine jurisdiction are represented within the protected area. Only 7 of the 11 seamount morphotypes are represented within the PIPA, with the proportion included ranging from 6% to 35%. Four of the seamount morphotypes (8, 9, 10, and 11) are represented at over 10%, which is in line with the Convention on Biological Diversity, Aichi target 11, adopted in Aichi, Japan, in 2010 (Convention on Biological Diversity 2010). The unrepresented and underrepresented seamount morphotypes should be prioritized for future management within Kiribati's national jurisdiction to fulfill Aichi target 11.

Clark and colleagues (2011) proposed the use of seamount classification schemes to assist in the development of marine protected area networks. The analysis presented in this chapter has been shown to have utility in addressing the representation of the different types of seamounts within existing spatially managed areas (the APEI of the CCZ and the PIPA). It can also be used to prioritize which features may require additional management measures based on their regional representation. For example, for countries to fulfil their commitments under Aichi biodiversity target 11 (Convention on Biological Diversity 2010), they are required to conserve through effectively and equitably managed, ecologically representative, and well-connected systems of protected areas and other effective area-based conservation measures and to integrate these protected areas into the wider landscapes and seascapes. In the absence of detailed information on the distribution of biodiversity, classifications such as the one presented here can help ensure that protected areas capture the full diversity of physical habitats as a surrogate for biological diversity.

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Supplemental Resources

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For the digital content that goes with this chapter, go to the following link or QR code. A hyperlink is also available in the book's online resources (esri.com/esripress-resources/ocean-solutions-2e).

Story Map App

- Mapping, Classifying, and Protecting Seamounts, <http://www.arcgis.com/home/item.html?id=ae4156bb0bec48aa82594eae453e453d>



This Story Map app provides an overview of seamounts: how they are officially defined as features on the ocean floor, how they are mapped and classified, and how they are an important foundation for marine habitat protection. The use of spatial data in habitat protection and marine spatial planning on and around seamounts is also a highlight of this Story Map app, with accompanying charts, maps, and a 3D interactive schematic of seamount morphotypes (as explained in this chapter).

CHAPTER 18^{New}

Satellite Services for Coastal Applications

Thomas Heege, Matthew Bergin, Knut Hartmann, and Karin Schenk

Abstract

The dynamic nature of coastal zones leaves them susceptible to dramatic change that can occur over time or even overnight. Numerous influences, both man-made and natural, combine to put great stress on coastal zones. Damages caused by dense human populations, coastal and offshore commercial activities, severe weather events, and even the normal wear of tides and currents challenge coastal zone management and create a great need for spatial and up-to-date environmental data.

Governmental organizations, such as space and environmental agencies, and commercial data providers help meet this need through satellite-based products and services that provide a wide range of relevant water information for coastal monitoring. Altimeter and synthetic aperture radar satellite sensor datasets provide information about water levels, sea states, oil films, and bathymetry in both deep and shallow areas. Multispectral optical satellite imagery helps identify objects and obstructions above and below the water surface. Multispectral optical satellite imagery can also be used to calculate a wide range of water-quality parameters, from turbidity, suspended matter, and chlorophyll concentrations to harmful algal bloom indicators to regionally calibrated biochemical components such as organic carbon.

The benefits of using satellite image analysis and services for coastal applications are showcased for mapping the shallow-water bathymetry of the Great Barrier Reef, the seafloor habitats of Abu Dhabi, and various inland water-quality and dredging monitoring sites. These case studies highlight the core advantages of these services: rapid data provision, spatial coverage in various spatial resolutions, high sampling frequency, and cost-effective service production. This chapter highlights examples such as the EOMAP web application (EOMAP 2015) and examines the geospatial portals and easy-to-use visualization tools that aid in effective analysis of, and access to, the big data derived from satellite data.

Introduction

The Demand for Coastal Monitoring Solutions

Coastal zones represent some of the most densely populated regions of the world and are under increasing pressure from man-made activities. Coastal zones are highly dynamic (Syvitski et al. 2005) and are subject to change in the short term (e.g., changes caused by extreme weather events) and long term (e.g., changes caused by erosion and currents). Furthermore, offshore and coastal engineering activities can modify coastal landscapes significantly, and man-made disasters can have dramatic impacts on the coastal environment. All these changes create a high demand for spatial and environmental data to aid in coastal zone management.

A consistent spatial framework is necessary and challenging, especially because the continually shifting land–water interface poses significant logistical problems for mapping (Committee on National Needs for Coastal Mapping and Charting 2004). The large area of Earth that is covered by water compounds the magnitude of this challenge. The extremely dynamic nature of coastal marine environments makes them especially difficult to monitor.

Important issues in coastal monitoring include water characterization, observations of water-quality trends over time, identification of emerging problems, and information for pollution prevention and emergency response (Siermann et al. 2014). By far the greatest demand is for up-to-date shallow bathymetric data (Committee on National Needs for Coastal Mapping and Charting 2004) to provide the fundamental geospatial framework, which is essential for navigation, port and offshore construction, security, coastal zone management, fisheries management, coastal restoration, and tourism. Vessel- and aircraft-based methods for conducting coastal monitoring surveys can be costly and time consuming, depending on the level of detail required. For these reasons, extended areas of water worldwide are not mapped in detail, or existing data may be out of date, especially in dynamic environments. The demand for bathymetric data is therefore obvious, and lack of this data causes risk to navigation and concerns to the offshore industry. The value-added services provided by satellite images can increasingly contribute to overcome geospatial data gaps and support continuous monitoring. As stated by International Hydrographic Organization president Robert Ward:

It is almost impossible to think, in the 21st century, that governments would produce sustainable economic development plans on the shore with no maps. But we seem to be doing it at sea, and we seem to have plans to continue. Of the 0–200m [depth] areas, 80% of West Africa, 95% of the southwest Pacific, and 95% of the polar regions are either unsurveyed, or require a new survey. (Bartlett 2013)

Satellite Monitoring Capabilities

Satellite-based products and services provide a wide range of relevant water information for coastal monitoring and are supported by governmental organizations, such as space and environmental agencies, as well as by commercial data providers. Altimeter and synthetic aperture radar (SAR) satellite sensor data provides information about water levels, sea states (Bruck and Lehner 2015), oil films (Singha et al. 2015), and bathymetry in deep- and shallow-water areas down to 10 m depth and at up to 150 m resolution (Pleskachevsky et al. 2011). Multispectral optical satellite imagery, which is the focus of this chapter, is used to determine shallow-water bathymetry that can in turn be used to identify objects and obstructions above and below the water surface. Multispectral optical

satellite imagery can also be used to calculate a range of water-quality parameters, such as turbidity, suspended matter, chlorophyll concentrations, derived trophic status information, harmful algal blooms, fractions of organic and inorganic absorbers, and related regionally calibrated biochemical components such as organic carbon.

Multispectral Satellite Images

Multispectral satellite sensors measure reflected sunlight, which is modified on its way through the atmosphere and the water column. Light is absorbed, scattered, and reflected as a function of particles, dissolved materials, and seafloor properties. In the water column, optically active components include suspended matter, phytoplankton, and their different absorbing pigments and detritus, as well as dissolved, colored organic matter (called “yellow substances” or *gelbstoff*). Using physics-based algorithms, quantitative values of the concentrations of optically active water components can be calculated. Such algorithms have been shown to be capable of delivering quantitative, standardized water-quality information across all relevant spatial and temporal scales (Malthus et al. 2012). Importantly, physics-based methods—as opposed to empirical methods—require no prior information of the study area (Heege et al. 2014). However, these methods are complex to develop in comparison with empirical methods, which remain limited to localized scales and usually cannot be applied to varying environmental conditions. It is crucial to understand the nature of the remote-sensing products, including limitations and their application range.

Satellite Resources

Various resolution requirements are supported through a combination of a wide range of multispectral satellite sensors. The Landsat 7, Landsat 8, Sentinel 2A, and Sentinel 2B satellites provide water quality information through global weekly measurements at 10 to 30 m resolution. NASA’s Aqua and Terra satellites, each equipped with a moderate-resolution imaging spectroradiometer (MODIS), provide global daily measurements at 0.5 to 1 km resolution; and the Sentinel 3 provides global daily observations at 300 m resolution. Consistent multitemporal information layers are accessible through online web apps such as the Esri Living Atlas of the World (Esri 2014) and eoApp (EOMAP 2015) at both intercontinental and local scales. Commercial high-resolution satellites such as Worldview, SPOT, Pleiades, RapidEye, Kompsat, and DubaiSat can be tasked for daily observations by request; and they provide information at 2 m resolution (figure 18.1). Past satellite missions such as Landsat 5 are capable of providing historic information over the last 30 years. However, the number and accuracy of accessible water-quality parameters depend not only on the processing methodology but also on sensor-specific characteristics such as sensor noise and the number and width of spectral bands. As long as the radiometric calibration is stable, basic parameters such as turbidity and total organic and inorganic absorption can be retrieved from most multispectral satellite sensors (Heege et al. 2014).

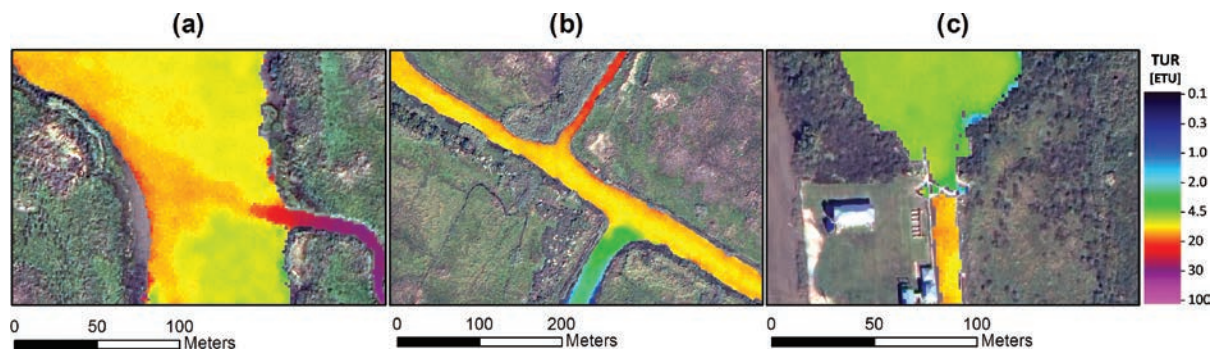


Figure 18.1. Commercial satellites provide high-resolution data for monitoring purposes. The example shows turbidity (TUR) concentrations in Earth observation turbidity units (ETU), similar to nephelometric turbidity units (NTU), in waterways southeast of New Orleans derived using WorldView-3 data, giving details about (a) inflow dynamics, (b) dispersion, and (c) barriers. Image by EOMAP © 2015, including copyrighted material of DigitalGlobe 2014.

Earth Observation Processing Infrastructures

Harmonized access to Earth observation resources will better support the exploitation of joint satellite capabilities. The intergovernmental Group on Earth Observations (GEO) largely addresses this need (Group on Earth Observations Secretariat 2005). Delivering time- and cost-efficient Earth observation services requires fast and low-cost access to large volumes of satellite data as well as effective data-processing streams. This requirement is especially the case for the upcoming Copernicus satellite fleet. If satellite data can be processed directly within the satellite receiving or archiving centers, or if there is a cost-effective data connectivity with commercial cloud-computing providers, efficient analysis of large data volumes is relatively simple. Bringing value-added processors to the data is a straightforward concept, as processors installed on virtual machines can easily be managed to support decentralized production capacities. EOMAP hosts distributed processing infrastructures within operational production chains on satellite ground segments in Europe, Australia, and Asia, as well as processor installations in commercial cloud-computing environments.

The need to derive valid and harmonized products can be met with generic sensor-independent approaches, covering a wide range of physics-based processing aspects. The Modular Inversion Processor (MIP) forms the basis of an operational sensor-independent production system. It includes algorithms optimized for coastal and inland waters, embedded adjacency correction, and fully coupled atmospheric-in-water retrieval of water constituents (Heege et al. 2014; Kiselev et al. 2014; Richter et al. 2014). It accounts for variable-specific optical properties and many more relevant impacts, such as shallow-water seafloor reflectivity. Products include ones that are compliant with the Open Geospatial Consortium (OGC) and the directive of the Infrastructure for Spatial Information in the European Community (INSPIRE), and International Standards Organization (ISO) standard 19115.

Satellite-Derived Bathymetric Surveying and Seafloor Mapping

The need for up-to-date bathymetric information is important for multiple applications, but this data is often not accessible, or it requires costly survey campaigns to collect. In this section, two case studies that demonstrate the use of satellite-based resources are highlighted: (1) shallow-water

mapping of the entire Great Barrier Reef and (2) seafloor mapping of Abu Dhabi, United Arab Emirates. Satellite image processing was conducted using EOMAP's MIP system (Cerdeira-Estrada et al. 2012). The algorithms used are bundled into function-specific modules. The modules are connected through a semiautomated processing chain, which also interrogates various databases for additional input. Briefly, image datasets are first preprocessed for land-water-cloud masking, adjacency correction, sun glint correction, and atmospheric correction. The processing stage involves the definition of water and seafloor bottom types, followed by a coupled retrieval of water depth based on the subsurface reflectance image. Postprocessing includes tide correction to lowest astronomical tide and a semiautomatic selection of correct depth retrievals as well as object-oriented processing of the seafloor reflectance information to develop seafloor habitat characterization.

Mapping of Australia's Great Barrier Reef

Australia's Great Barrier Reef (GBR) is of international importance. Despite the need to monitor, manage, and protect this World Heritage Area, the broad-scale, environmental baseline information available to date has been surprisingly incomplete. Nearly half the shallow-water reef area of the GBR had not been mapped using modern digital surveys until recently. Although these shallow coral reefs are ecologically significant, they are the most difficult to map because either they are too remote or their shallow nature makes them dangerous to navigate. Instead of relying on traditional survey vessels or aircraft to map these areas of the reef, EOMAP used Landsat 7 satellite imagery from 1999 to 2003.

The final result was a digital, high-resolution, shallow-water bathymetric map of the entire GBR. The product has a nominal vertical resolution of 10 cm and a horizontal resolution of 30 m. A new version of this dataset is planned for 2016, using the most recent satellite imagery from the Landsat 8 and Sentinel-2 missions. In addition, as the processing system is sensor agnostic, a high-resolution bathymetric grid of 1 to 3 m spacing and additional seafloor characterization can be provided for every location of the reef using commercial satellite imagery. An example of this detail can be seen in figure 18.2.

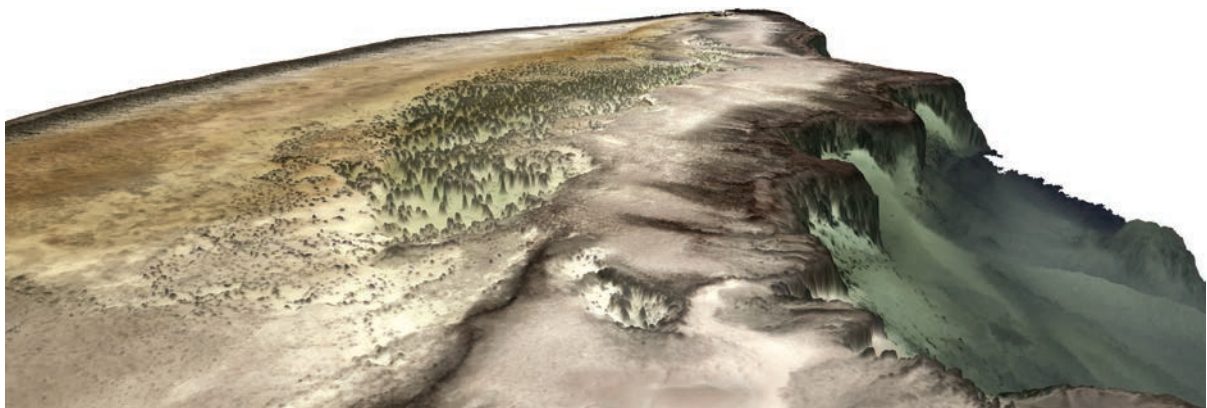


Figure 18.2. High-resolution seafloor reflectance is draped over satellite-derived bathymetry at Heron Island Reef, Australia. Image by EOMAP © 2015, including copyrighted material of DigitalGlobe 2013.

Using satellite imagery to estimate bathymetry can dramatically improve the foundational spatial data used for the GBR (e.g., Beaman et al. 2012). It can provide the basis for a range of derived map products used by government agencies for monitoring, management, and planning; by research institutions for monitoring and modeling; and by private industry to build its own applications for the data (e.g., Phinn et al. 2000).

Bathymetry and Seafloor Habitat Classification in Abu Dhabi

The same key drivers as the GBR project motivated bathymetric mapping and seafloor habitat classification in Abu Dhabi, including the demand for spatial and up-to-date information for coastal areas. In 2013, the Environmental Agency Abu Dhabi (EAD) initiated a multiyear program aimed at creating fine-scale habitat maps for its entire coastal environment, as well as land-use information. The objective was to provide fundamental data layers for decision-making and sustainable management. EOMAP mapped the seafloor based on RapidEye and WorldView-2 satellite imagery (Environmental Agency of Abu Dhabi 2014). The benthic habitats were classified using seafloor reflectance information following an object-based classification approach (Blaschke et al. 2014). In total, 11 habitat classes were defined down to a depth of 15 m. The classifications followed the accepted schema developed by the National Oceanic and Atmospheric Administration (NOAA) and the Coastal and Marine Ecological Classification Standard (CMECS). In addition, a 5 m bathymetric grid was derived from satellite data, providing depth information for areas of Abu Dhabi that were not previously sufficiently surveyed.

Resulting mapping products are available through the EAD online portal (<http://enviroportal.ead.ae/mapviewer>) (figure 18.3). The classifications of the seafloor habitats showed an overall fit of 85% and were validated against 58 independently sampled in situ data collections. The classification of approximately 30,000 sq km was performed in 16 months.



Figure 18.3. Seafloor classification of Abu Dhabi performed by EOMAP is visualized in the online portal of the Environmental Agency of Abu Dhabi. Image by the Environment Agency of Abu Dhabi © 2015.

Regular updates of this high-resolution baseline can now be easily supported through upcoming high-resolution satellite imagery. This imagery is of particular importance for areas in which dredging or other offshore activities significantly change the seafloor and its ecosystem (figure 18.4). An increasing number of official baseline maps are supported by satellite data. Extended coastal surveys have been provided for a number of coastal zones using remote-sensing data and the

harmonized data-processing approach of EOMAP (e.g., in Australia for the Ningaloo Reef in collaboration with Murdoch University and the Commonwealth Scientific and Industrial Research Organisation [CSIRO] [Kobryn et al. 2013], as well as Rottnest Island close to Perth; in Mexico for the whole Yucatan coastline down to Belize; and in Europe and the Middle East for offshore construction surveys).



Figure 18.4. Imagery shows satellite-derived underwater and land topography in the shallow waters surrounding Al Quaffay island, United Arab Emirates. This region has been modified by dredging activities, clearly visible as deep channels in the *upper* part of the image, in shallow water and land areas. Image by EOMAP © 2015, including copyrighted material of DigitalGlobe 2013.

High-Resolution Spatial and Temporal Water-Quality Monitoring

Integrated water-quality data with high temporal frequency and large spatial coverage are essential for reducing water monitoring costs and optimizing in situ monitoring strategies, increasing knowledge about the status of areawide surface waters, and evaluating long-term changes related to human impacts as a result of infrastructure, changes of land-use trophic status, and climate change (European Commission 2012).

The applications in which satellite data is needed for water monitoring are manifold. Government authorities responsible for water quality need reliable and up-to-date data on a regular basis to assess a variety of physical and biological parameters in aquatic ecosystems. Industry also requires water information for many reasons. For example, oil and gas companies as well as dredging organizations operating in marine environments need data for their offshore operations. And the fishing and aquaculture industry must find suitable sites to operate their businesses. The following sections provide brief overviews of three case studies: dredging monitoring in Australia, waterways management in Germany, and environmental assessment in Italy, each supported by satellite-derived services.

Dredging Monitoring: Australia

Woodside Energy, an Australian oil and gas company, sought a water-quality monitoring solution to satisfy regulatory requirements for pipeline dredging operations. EOMAP implemented a cost-effective satellite-based turbidity mapping solution. Water turbidity products of an area in North Western Australia were provided for more than two years for an area approximately 1,000 sq km. On average, a quality-controlled turbidity map from one of the MODIS satellites was delivered every two days at 250 m resolution. The previously described physics-based processing approach using MIP was applied with an algorithm to fuse the 500 m multispectral bands with the 250 m MODIS band. These datasets complemented the localized, point-based environmental monitoring strategy of Woodside's Pluto liquefied natural gas development project with spatially resolved distribution maps. The cost savings for this project alone, when compared with an aerial monitoring solution, was AUD 1 million. Reliable and robust quantitative map products helped to avoid delays in the dredging operation. In addition, health, safety, and environment risks were avoided completely, because no field operations were required and no environmental impacts were generated using the satellite monitoring solution.

River Management: Germany

The German Federal Waterways Engineering and Research Institute (BAW) applied water-quality maps to optimize waterway engineering in the estuaries of the River Elbe. Regularly recorded turbidity and suspended matter maps derived from Landsat 5, 7, and 8; from the MODIS-equipped Aqua and Terra; and from RapidEye satellites were used. Understanding the transport processes of suspended sediments in waterways is essential to reduce river engineering expenses such as dredging, in which roughly 1 million m³ are moved annually between Hamburg and the North

Sea. Measurements in combination with three-dimensional hydrodynamic modeling are a key to understanding the processes and optimizing engineering works. The areawide remote-sensing products of suspended matter give very valuable synoptic measurements of suspended matter surface concentrations.

Environmental Monitoring: Italy

The Department for the Protection of the Inland and Marine Waters Marine Service of the National Italian Institute for Environmental Protection and Research (ISPRA) evaluates the environmental impact of a gas power plant built next to the River Po in Italy. Its influence on water-quality parameters such as total suspended matter, chlorophyll-a, and organic absorption is monitored on a daily and weekly basis using medium- and high-resolution satellite imagery from MODIS satellites and Landsat 7 and 8. Figure 18.5 shows the highly dynamic River Po estuary in Italy.

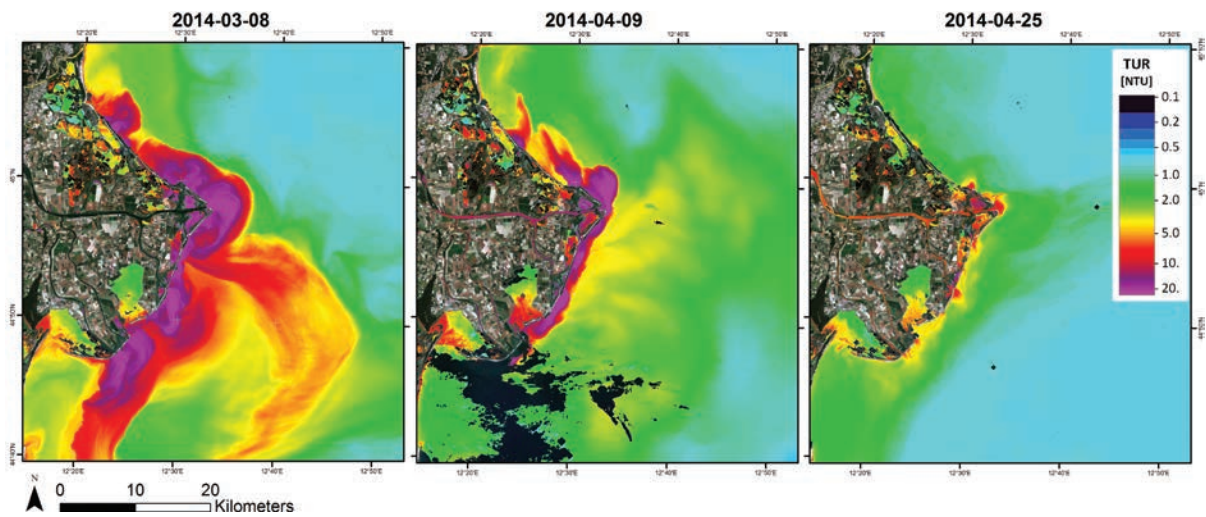


Figure 18.5. Temporal and spatial dynamics in aquatic environments can be made visible using satellite-derived water-quality products. The example shows turbidity products derived using Landsat 8 satellite data for the River Po estuary in Italy for three different dates: March 8, April 9, and April 25, 2014. Image by EOMAP © 2014, including data of the US Geological Survey 2014.

Conclusion: Importance of Geospatial Portals

Key to using the described monitoring capabilities of Earth observation beyond the integrated multisensor data processing capability are easy uptake and aggregation of data to higher product levels and synthesis of generated information products. User-friendly geospatial data access portals and geospatial analysis tools are required in a variety of solutions that suit the needs of different client preferences and workflows. Many users are not yet familiar with geospatial software and require easy access to information layers. Web apps can adapt to this requirement, supporting a minimum of basic functionalities to keep it simple. The EOMAP eoApp (EOMAP 2015) web app follows this concept and provides easy access to recent and historic information layers (figure 18.6a, Australia coastal time series, and figure 18.6b, inland waters in Florida), which are automatically updated on a daily basis.

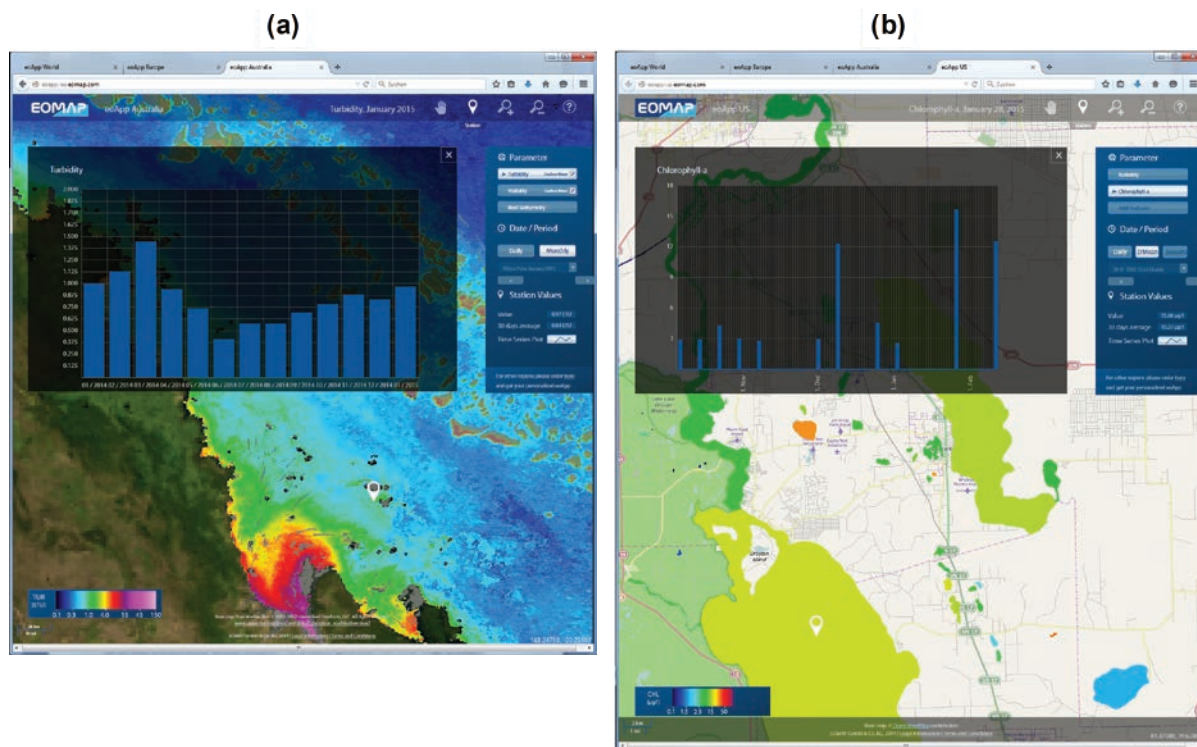


Figure 18.6. Examples of the EOMAP eoApp (EOMAP 2014, 2015): (a) monitoring of daily turbidity in 500 m resolution in Abbot Point, Australia, and (b) monitoring of weekly chlorophyll-a in 30 m resolution for several lakes in Florida. Trends in concentrations over time can be viewed in the time-series plots for selected stations. Image by EOMAP © 2015, including data from the US Geological Survey and the National Aeronautics and Space Administration 2014.

Thanks to OGC and ISO 19115 metadata standards, harvesting multiple information products into a generalized geospatial platform is now easy to do. Comprehensive thematic platforms such as the Esri Living Atlas of the World (Esri 2014) and the Esri Hydrographic Office portal can be used to integrate all access, visualization, and analysis of various environmental data sources (figure 18.7). Finally, the success of turning information to knowledge and understanding of marine processes is driven by a multidisciplinary approach, combining multiple data sources including the space observation technologies, modeling, and geospatial information technology solutions.

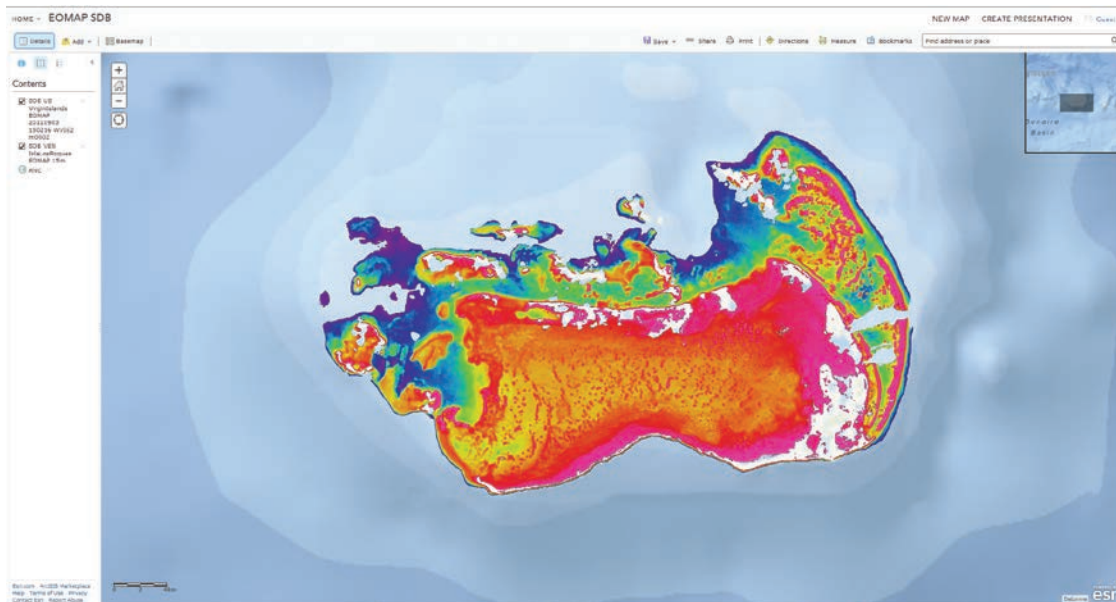


Figure 18.7. Satellite-derived bathymetry of a reef in Los Roques National Park in Venezuela is displayed in the Esri online map service of the Esri Hydrographic Office team based on Landsat 8 data. Image by EOMAP © 2015, including data from the US Geological Survey 2015. Basemap data sources: Esri, GEBCO, NOAA, National Geographic, De Lorme, HERE, Geonames.org, and other contributors.

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CHAPTER 19^{New}

The Coastal Defense App: Evaluating Nature's Role in Coastal Protection

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Abstract

Coastal Resilience, especially as exemplified by the Coastal Resilience network (The Nature Conservancy 2015c), is an approach that guides decisions to reduce the risks of coastal hazards and identify nature-based solutions. Since it began in 2008, the approach has evolved over seven years of on-the-ground work, scientific research, tool development, stakeholder engagement, and policy implementation with significant investments in several successful demonstration sites. This approach is communicated through the Coastal Resilience web-based mapping tool. The tool, originally designed as a simple data viewer, now implements a flexible, robust mapping platform and browser-based apps designed to examine coastal hazards and social, ecological, and economic assets. Coastal Resilience contains a modular plug-in architecture, allowing apps to be designed and deployed by the open source community and plugged into the platform. Since 2013, The Nature Conservancy; University of Southern Mississippi; University of California, Santa Cruz; the Natural Capital Project; and Azavea have developed apps across a variety of geographies in the United States and internationally. The most popular and in-demand app, named Coastal Defense, quantifies how habitats protect coastal areas by decreasing wave-induced erosion and inundation. This app helps stakeholders identify appropriate nature-based solutions to reduce risk and increase community resilience. The coastal protection model from the Natural Capital Project's Marine Integrated Valuation of Environmental Services and Tradeoffs program runs within the Coastal Defense app to calculate the reduction of wave height and wave energy in the presence of coastal habitats. An essential element of Coastal Defense is ensuring that community stakeholders, decision-makers, and practitioners understand the app and how it can inform a particular planning process. To date, Coastal Defense has been deployed in three places: Puget Sound, Washington; Mobile Bay, Alabama; and Southeast Florida. These geographies are demonstration sites in which the app supports coastal erosion issues, restoration strategies, and nature-based adaptation solutions. The Coastal Defense app can be deployed at various scales and customized to meet decision support needs in various ecological, social, and economic settings. In September 2014, Coastal Defense was announced as the best app in the Professional and Scientific category for the Global Resilience

Disaster App Challenge run by Esri and the United Nations Office of Disaster Risk Reduction. And in May 2015, the app was selected as a finalist in the Prize for Progress, an award given by the American Society of Adaptation Professionals.

Introduction

More and more people in all parts of the world are exposed to floods, drought, earthquakes, and cyclones (Beck and Shepard 2012). Floods and extreme weather events affect not only people but the infrastructure they depend on. The rate of coastal development and climate change are rapidly changing the world's coastlines and dramatically increasing risks of catastrophic damage (Beck 2014).

Habitat degradation raises these risks by further exposing coastal communities and assets to more waves, winds, and water. Decision-makers can reduce risk to their communities only if they have access to the information required to make smart development decisions (Ferdaña et al. 2010; Groves et al. 2012). In an effort to arm stakeholders with the information they need to guide adaptation and mitigation strategies, The Nature Conservancy (TNC) and a core group of partners—including the National Ocean and Atmospheric Administration (NOAA); US Geological Survey (USGS); Natural Capital Project (NatCap); Association of State Floodplain Managers (ASFPM); University of California, Santa Cruz (UCSC); University of Southern Mississippi (USM); and Azavea—originally developed Coastal Resilience in 2008, with version 2.0 released in 2013.

Coastal Resilience is an approach and decision support tool framework that provides stakeholders with a stepwise process to reduce the ecological and socioeconomic risks of coastal hazards, as follows:

1. **Assess risk and vulnerability** to coastal hazards by including current and future storms and sea level rise.
2. **Identify solutions** for reducing risk that benefit social, economic, and ecological systems.
3. **Take action** to help communities develop and implement these solutions.
4. **Measure effectiveness** to ensure that efforts to reduce risk through restoration and adaptation are successful.

Giving communities the information they need to find the most cost-effective and multibeneficial solutions, Coastal Resilience focuses on bringing natural infrastructure into the risk reduction equation (Beck et al. 2013). Although risk reduction strategies vary on the basis of local factors and planning processes, all too often decisions are made to invest in traditional coastal defenses such as sea walls, dikes, or groins (“gray infrastructure”) without weighing the costs and benefits of other options. Gray infrastructure refers to highly engineered defenses that use hard materials such as concrete, rock, or wood to hold off advancing sea levels and storm surge or to control the flow of storm water. Although this type of infrastructure helps safeguard our communities, it is often expensive and single purpose, and it incurs high maintenance costs over time. Gray infrastructure can also have several socioeconomic and ecological drawbacks, such as blocking public access areas; causing loss of beaches and coastal habitats; and interrupting natural coastal processes, which inhibits habitat migration and prevents natural adaptation. “Green,” or natural infrastructure, such as beaches and dunes, marshes and mangroves, and coral or oyster reefs, provides soft-engineered solutions, such as living shorelines, that also provide other community benefits (figure 19.1). Natural coastal defenses intercept waves, which helps decrease wave height and power, thereby reducing coastal erosion. Natural defenses also provide other ecosystem services or cobenefits, including enhanced fisheries, sustainable food security, and increased water quality. By incorporating nature-based solutions, communities can achieve multiple economic, social, and ecological benefits while addressing risk reduction (Hale et al. 2009; Hale et al. 2011; Spalding et al. 2012; Arkema et al. 2013).



Figure 19.1. Low tide exposes the oyster reefs in Corpus Christi Bay in Port Aransas, Texas. Oyster reefs are natural breakwaters that can stabilize shorelines, help to build wetlands, promote local fisheries, and improve water quality by reducing runoff and suspended sediment in the water column. Photo courtesy of Erika Nortemann, The Nature Conservancy, 2010.

As an online decision support tool, Coastal Resilience provides local, state, and national planners a stepwise process to guide decisions to reduce the ecological and socioeconomic risks of coastal hazards. The Coastal Resilience tool operates from global to local scales for more detailed planning in more than a dozen states and numerous communities. It supports a network of practitioners around the world who are applying innovative nature-based planning approaches and web-based decision support tools to coastal hazards and adaptation issues. For example, the tool has been instrumental in guiding decisions for Connecticut state policy, including the development of a sea level rise task force, coastal development in Southern California, and restoration decisions in the Gulf of Mexico. Coastal Resilience is also applied internationally in places such as Grenada for assessing social and ecological vulnerability in partnership with the Red Cross, and globally to develop USAID Coasts at Risk indicators and a World Risk Index with Alliance Development Works.

The network of practitioners who are applying the Coastal Resilience approach and tool has rapidly expanded to include 14 US coastal states (Alabama, California, Connecticut, Florida, Hawaii, Louisiana, Maine, Mississippi, New Jersey, New York, North Carolina, Texas, Virginia, and Washington), four countries in Latin America (Mexico, Belize, Guatemala, and Honduras), and in three island nations in the Caribbean (Grenada; St. Vincent; and the Grenadines, US Virgin Islands). There are also global and US national web apps that together form the Coastal Resilience network (figure 19.2). The entire suite of geographies can be found at The Nature Conservancy (2015b).

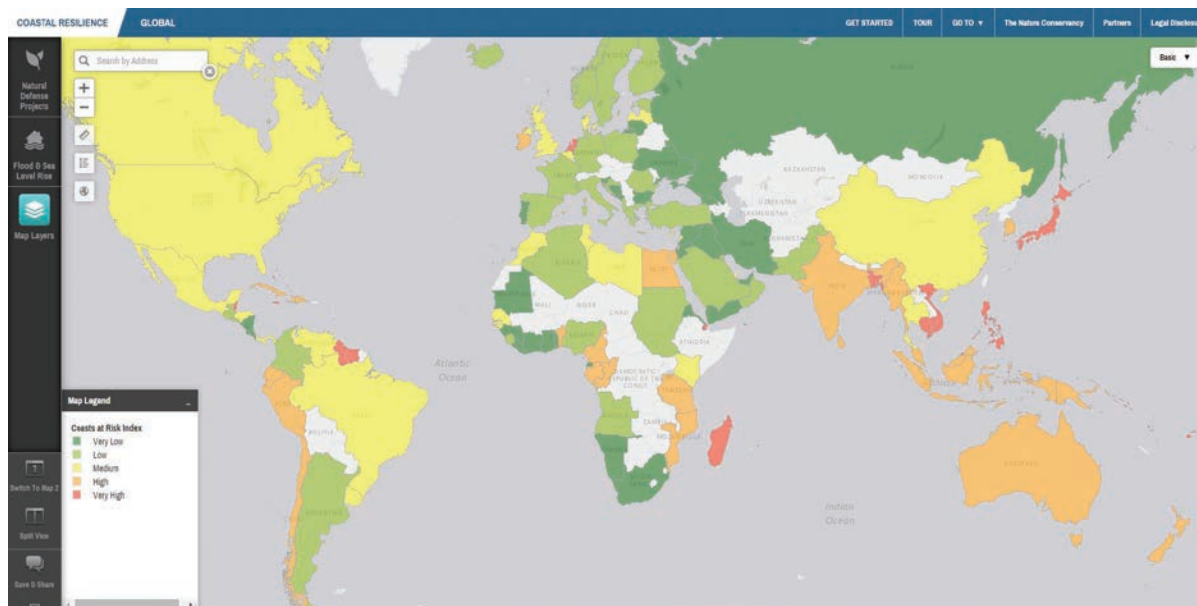


Figure 19.2. The flexibility of the Coastal Resilience mapping tool framework allows for the development of web apps that have local to global reach, such as the global Coasts at Risk Index shown here. Graphic created by The Nature Conservancy 2015.

Coastal Resilience Decision Support Tool

Using the ArcGIS API for JavaScript, the mapping tool framework, and a suite of apps, or plug-ins to the framework, delivers a consistent look and feel across all Coastal Resilience project areas. Licensed under a GNU General Public License, version 3, on October 7, 2013, the Coastal Resilience tool is open source, although there are some terms for its use and modification (The Nature Conservancy 2013). The modular system architecture of Coastal Resilience allows communities to develop customized apps that address specific coastal risk, restoration, and adaptation issues.

The Coastal Resilience suite of apps helps communities examine risk and vulnerability assessments and understand where viable nature-based solutions play a significant role in reducing this risk. What sets it apart from other web-based decision support tools is that it is more than simply a data viewer. Coastal Resilience has found its niche by offering collaboratively designed open source apps that allow users to integrate coastal hazards with social, ecological, and economic data for use in risk, restoration, and adaptation planning. Apps target specific coastal issues, including assessing the ability of marshes to migrate landward with sea level rise, oyster reef restoration suitability, potential economic exposure and loss estimations with sea level rise and storm surge, and the value of natural habitats in protecting a community's coastal assets. The tool framework of Coastal Resilience allows a community to assist in the design and review an app as it is being developed to ensure its usability and effectiveness. These apps are developed with a host of academic, government, and nonprofit partners that work from local to global scales to inspire action to reduce risk and promote resilience. Because the apps are open source, they can be transferred to different ArcGIS API for JavaScript platforms, extending their use to other environmental, social, and economic decision support tools.

Coastal Resilience Framework

Regions

The Coastal Resilience web mapping tool framework is built to accommodate functionality at several geographic scales from global to the community level. The highest level of organization within the framework is referred to as a “regional site,” or a small ASP.NET program that serves a JavaScript client and that is configured and loaded with plug-ins to operate on any geographic extent. All geographies are created from the same framework code base and are customized for each region by adding custom configuration files, graphic assets, and plug-ins, also called *apps*. The plug-ins are similarly configured to operate on the specific data that is relevant to the site in which they are deployed. The app processing is almost entirely client side, which results in very low resource requirements. Larger amounts of server resources are devoted to the ArcGIS for Server instances for geoprocessing and mapping tasks, which, for the most part, are consumed by the plug-ins.

Plug-ins (Apps)

Conceptually, a plug-in is a bundle of JavaScript code and companion resources (Cascading Style Sheets [CSS], images, and so on), which displays a custom HTML-based user interface (UI) for collecting data from the user, optionally makes requests to map and geoprocessing services, and displays results by creating layers and adding these layers to a common full-page map. Plug-ins are not restricted to using only the JavaScript libraries that the framework app will use, but are allowed to load and use any JavaScript libraries they need to create their UI and process their tasks. Further, plug-ins include their own configurations to interact with ArcGIS resources. Each plug-in communicates directly with the ArcGIS for Server instances, primarily through the representational state transfer (REST) interface for the services, either directly or through the ArcGIS for JavaScript API wrapper. Plug-ins have been developed to suit a range of needs from generic to specific. For example, a table of contents-style plug-in, measure tool, and basic navigation plug-ins are deployed in almost every region. Other plug-ins guide the user through more specific tasks, such as assessing risks or examining socioeconomic and habitat vulnerability. The Coastal Defense app is one of the larger and more complex plug-ins currently deployed in Coastal Resilience. The details of this app are discussed later in this chapter.

Server Application

The site is an ASP.NET MVC application served from IIS running on a Windows Server with the Microsoft .NET Framework, version 4.0 installed. Each regional site comprises template pages and configuration files for the region itself, as well as the same for the specific plug-ins that are defined for the region. Once constructed, the main site page for a region remains completely static until an administrator makes modifications to the configuration. This arrangement allows for an aggressive caching strategy, resulting in a highly scalable design. Regional sites do not perform any processing, authentication, session management, or other persistence on the server, so there are no other server dependencies to the application framework except a simple key-value store that is used to store permalink hashtags. The regional site installation itself does not have any dependencies on ArcGIS for Server directly. The default basemaps are served from ArcGIS Online but can be configured to

use any map service provided by an ArcGIS for Server instance. The bulk of the interaction with ArcGIS for Server is performed by the separately configured plug-ins. The framework client web app depends on several libraries, including ArcGIS API for JavaScript 3.2, Dojo 1.7.3, and various utility libraries, such as backbone.js and underscore.js.

Coastal Defense

The Model

The presence of coastal habitats such as sea grass, marsh, coral or oyster reefs, and mangroves decreases water depth and forces oncoming waves to break before they would otherwise (Shepard et al. 2011; Zhang et al. 2012; Ferrario et al. 2014). This wave action results in smaller and less energetic waves shoreward of the habitat and decreased wave run-up on shore. In this way, coastal habitats can help protect nearby communities by acting as natural breakwaters, reducing shoreline erosion and lowering potential risk to people and infrastructure (Guannel et al. 2015). The most commonly used method of evaluating the protective benefits provided by coastal habitats is measuring wave height attenuation (Suzuki et al. 2012).

The core functions of the Coastal Defense app come from NatCap's Coastal Protection model, which is freely downloadable through the open source Marine Integrated Valuation of Environmental Services and Tradeoffs (InVEST) program software suite. The model combines information on the location and physical characteristics of coastal habitats with offshore wave data, bathymetry, and nearshore topography to quantify how their individual and cumulative presence can reduce the amount of shoreline erosion and inundation (Sharp et al. 2014). The InVEST Coastal Protection model is composed of two submodels: the Profile Generator and the Nearshore Wave and Erosion model (figure 19.3).

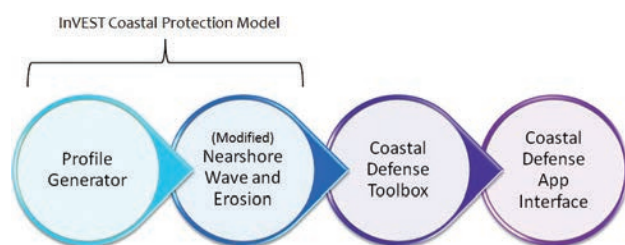


Figure 19.3. The process workflow describes how the Marine Integrated Valuation of Environmental Services and Tradeoffs (InVEST) Coastal Protection model is incorporated into the Coastal Defense app.

Graphic created by The Nature Conservancy, 2015.

The Profile Generator is a stand-alone executable tool that uses bathymetry, topography, and habitat presence data to estimate the benthic characteristics of the nearshore environment that are required input for the wave model. The Profile Generator creates one-dimensional cross-shore profiles perpendicular to the shoreline for the entire area of interest, down to the resolution of 250 m apart. Each profile includes the elevation and habitat presence along the length of the transect. The tool also calculates the maximum fetch distance at the shoreline for each of the 16 equiangular directions that make up the compass rose, which can be used to generate wave characteristics.

The Nearshore Wave and Erosion model combines the output from the Profile Generator tool with user-defined offshore wave characteristics to quantify how the presence of coastal habitats can reduce shoreline erosion and inundation. If directly downloaded from InVEST, this model requires the user to acquire and format the data, perform the modeling, and troubleshoot outputs. Coastal Defense uses a modified version of the Nearshore Wave and Erosion model that provides more flexibility by preprocessing and quality checking all inputs and outputs. First, the Coastal Defense wave model simulates the evolution of a wave that originates in deep water and encounters habitat patches as it progresses shoreward along the one-dimensional profile. To accomplish this simulation, the model requires preprocessed wave statistics that include average, 95th percentile (storm), 98th percentile (strong storm), and maximum wave strengths. These statistics can be derived from either observed wave data via offshore buoy stations or modeled wave data such as NOAA Wavewatch III (National Weather Service 2009). However, for small, sheltered estuaries or bays that may not have these types of wave data available, the fetch distance output from the Profile Generator tool can be combined with a time series of local wind speed and wind direction data to create wind-generated waves to fill this data gap.

The Coastal Defense model can also incorporate different water levels on which the simulated wave occurs. Averaging all active NOAA tidal benchmarks near the area of interest generates local tidal levels. Potential sea level rise categories are gathered from observed relative measurements or downscaled global models. Where applicable, hurricane wave strengths are based on the wind and wave thresholds documented in the Saffir-Simpson scale (Simpson and Saffir 1974). Extreme hurricane conditions are normally not considered because the effect of any natural infrastructure option is negligible under the associated forcing conditions. However, coastal habitat protection under less severe or more frequent storm events is considered to have a more significant impact on wave attenuation.

Next, the model uses standard engineering equations to compute the changes in wave height and wave energy in the presence and absence of the coastal habitat(s) of interest as well as changes in erosive forces that act on the seabed. It computes the wave height shoreward of the habitat as a function of the wave height immediately offshore of the habitat via a transmission coefficient. The value of the coefficient is a function of the geometry of the habitat, as well as the height and period of the incoming wave. For example, the geometry of an oyster reef includes height, base, and crest width, whereas vegetative habitats are physically represented by vertical cylinders of uniform diameter (Dalrymple et al. 1984). When waves encounter a habitat, they exert a horizontal drag force in the cross-shore direction. The model can evaluate the individual and cumulative wave attenuation services of several types of habitats, including coral or oyster reefs, marsh, sea grass, sand dunes, mangroves (figure 19.4), and submerged artificial structures such as reef balls, used to simulate reef habitat. For each habitat type, the model requires various representative characteristics such as height, stem diameter, and stem density. If locally observed values are not available, the InVEST Coastal Protection model user's guide (Sharp et al. 2014) provides common plant characteristics and drag coefficient values based on US Federal Emergency Management Agency guidelines (Federal Emergency Management Agency 2007).



Figure 19.4. Red mangrove roots reaching into shallow coastal waters. Mangroves stabilize the shoreline; provide buffers from storm surges; trap debris brought in by tides; and provide feeding, breeding, and nursery grounds for a great variety of fish. Photo courtesy of Mark Godfrey, The Nature Conservancy, 2009.

Model Strengths

The Coastal Defense model's strengths include the following:

- The model quantifies and evaluates the amount of wave energy and potential erosion reduction associated with the presence of various types of coastal habitats.
- The modular functionality of this model allows it to be quickly applied in various geographies, either broadly, using default data, or site-specifically when local data is available.
- The model is capable of evaluating multiple habitat types, such as coral reefs, marshes, oyster reefs, sea grass, and mangroves. It can also calculate the cumulative wave attenuation services that multiple habitats provide.
- The user can measure the effects of coastal habitats on reducing risk to various types of coastal infrastructure such as earthen levees, seawalls, and bare shorelines.

Model Limitations

The Coastal Defense model's limitations include the following:

- The model simplifies wave propagation along a one-dimensional transect perpendicular to the shore, and therefore two-dimensional processes including longshore currents are assumed negligible.
- Habitat length and directional placement offshore are not currently addressed.
- The model estimates coastal protection services provided by habitats in terms of the reduction in damages as a result of erosion from storm waves, not surge.

- This model is not validated and predictive but is meant to provide guidance to stakeholders as an informative tool for planning. More model development and local calibration are required to address specific place-based restoration, conservation, or adaptation strategies.

The App

The Coastal Defense app was designed to provide a graphical user interface (GUI) that allows users to quantify how different coastal habitat scenarios alter water levels and erosive forces under various sea levels, tidal heights, and storm wave conditions, both now and in the future. Coastal Defense embeds the wave model within the app, in which users can interact with the parameters and specify particular scenarios on the fly through custom geoprocessing services. In this way, Coastal Defense helps support scenario planning and interactive stakeholder engagement by helping to visualize and make the case for nature-based solutions in coastal development and land-use planning.

The Coastal Defense GUI helps users (1) identify areas that may be at risk of coastal erosion and inundation from wave action and storms; (2) interactively examine the role of coastal habitats in attenuating wave height and energy; and (3) determine appropriate adaptation strategies that incorporate green (habitats) and gray (seawalls and other man-made structures) infrastructure trade-offs.

The app interface can be customized to give users the ability to specify criteria such as wave and storm characteristics, the tidal or sea level at which the wave occurs, the location of restored or degraded coastal habitats, and the location of built infrastructure for exploring hybrid green/gray solutions. The most recent version of the app interface was developed for Southeast Florida and uses ArcGIS API for JavaScript to allow for ready access to input parameters within the Coastal Defense model, which is now exposed as a geoprocessing service. The geoprocessing service and Coastal Defense GUI can be deployed at various scales and combine various coastal habitats to illustrate their cumulative protective benefits.

To begin, users select a region of interest from a drop-down list. The map viewer then automatically zooms to the desired extent, in which users are prompted to click a location within specified subregions on the map where they would like to explore different scenarios. A cross section of the one-dimensional transect at that location then populates in the GUI and displays the depth profile and the location of existing habitat types.

Users are then guided to select from several types and intensities of forcing conditions to generate the modeled wave (table 19.1). Users can also select the height of the sea surface at the time the simulated wave occurs (table 19.2). All these categories are derived from the preprocessed wave statistics and water levels discussed in the previous section.

Table 19.1. User-Selected Forcing Condition Parameters in the South Florida Coastal Defense App

Wave Condition Types	Oceanic	Wind-Generated Wave	Hurricane
Wave Strength	Average	Average	Tropical Storm
	Storm	Storm	Category 1
	Strong Storm	Strong Storm	Category 2
	Maximum	Maximum	Category 3
			Category 4

Source: The Nature Conservancy 2015.

Table 19.2. User-Selected Sea Level Parameters in the South Florida Coastal Defense App

Tidal Level	Sea Level Rise
Mean Lower Low Water	Low
Mean Sea Level	Medium
Mean Higher High Water	High
Highest Observed	

Source: The Nature Conservancy 2015.

After selecting the desired forcing conditions, users can simulate a future habitat restoration or degradation scenario, adding or subtracting habitat coverage by typing the width of the habitat footprint or using interactive slider bars located above the cross-section profile (figure 19.5). The artificial reef structure habitat type allows users to use the slider to place the structure at a specified distance offshore, as well as to select the type and dimensions of the proposed reef.

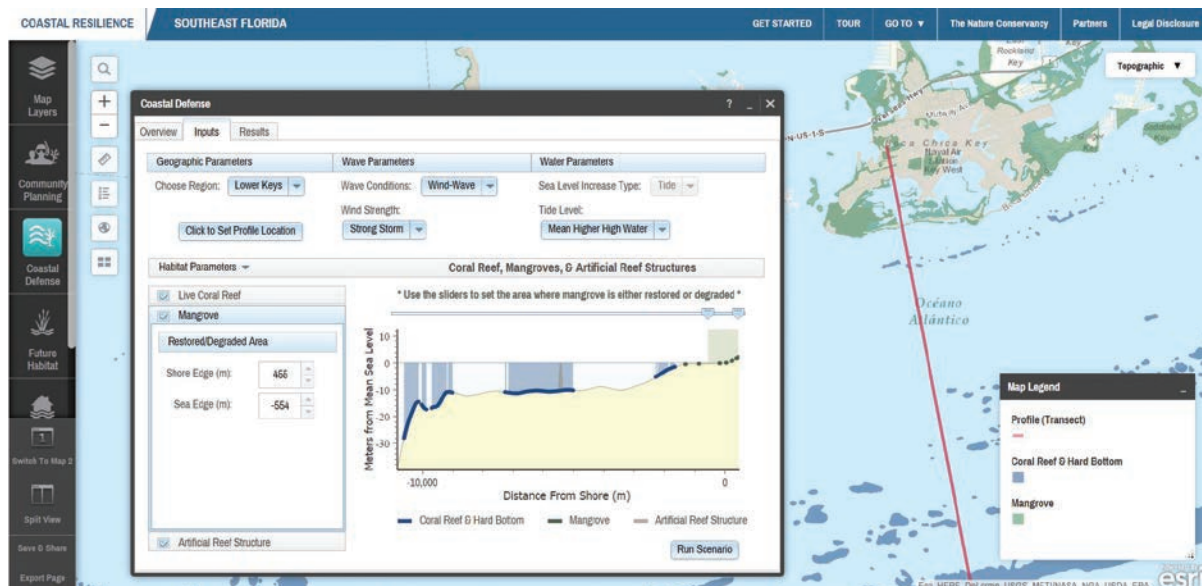


Figure 19.5. In Southeast Florida, the Coastal Defense app interface shows the presence of existing coral reefs and mangroves along the chosen transect. Users can use the slider bars above the cross-section graphic to modify the width of each habitat to model a degradation or restoration scenario. Image by The Nature Conservancy © 2015. Data sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors.

When a user decreases the extent of existing habitat, the model assumes the area that was once covered by that habitat type is now exposed, resulting in a decrease in the overall drag and wave attenuation provided by that habitat. This decrease might be the case when simulating the damage or removal of an existing habitat. When a user increases the extent of an existing habitat, the model assumes the area is now covered by that fully established habitat type, resulting in an increase in overall drag and wave attenuation provided by that specific habitat. For example, a user can simulate the impacts of the restoration of a mangrove forest by using the sliders to increase the extent of existing mangroves. Similarly, a user can explore the restoration of coral reef on existing benthic areas that can support its growth (e.g., hard bottom). Such common scenario workflows can be translated into

customized “storylines” to help organize scenarios within the app interface. The development of these storylines is an iterative process, which is heavily guided by stakeholder engagement.

Once satisfied with the scenario created, the user can run the model by clicking the Run Scenario button and instantly review the results. Programmatically, a user’s choice in forcing and habitat conditions is translated into the corresponding parameters expected of the Coastal Defense wave model, which is exposed as an ArcGIS for Server geoprocessing service. Parameters are posted to the custom geoprocessing service for execution on the server using the ArcGIS for JavaScript API and retrieved by the client’s browser when successfully executed. Upon completion, the app interface dynamically renders a graph of wave height before and after the habitat scenario, the percentage of overall wave attenuation, and the location of habitat(s) along the one-dimensional profile for comparison (figure 19.6). Ancillary output graphs are available through an HTML page that can be customized to include erosion probability, sensitivity analyses, or probability of structures overtopping. Different scenarios can be easily explored by changing one or more inputs from the previous run of the model and resubmitting it to the server for subsequent processing and retrieval.

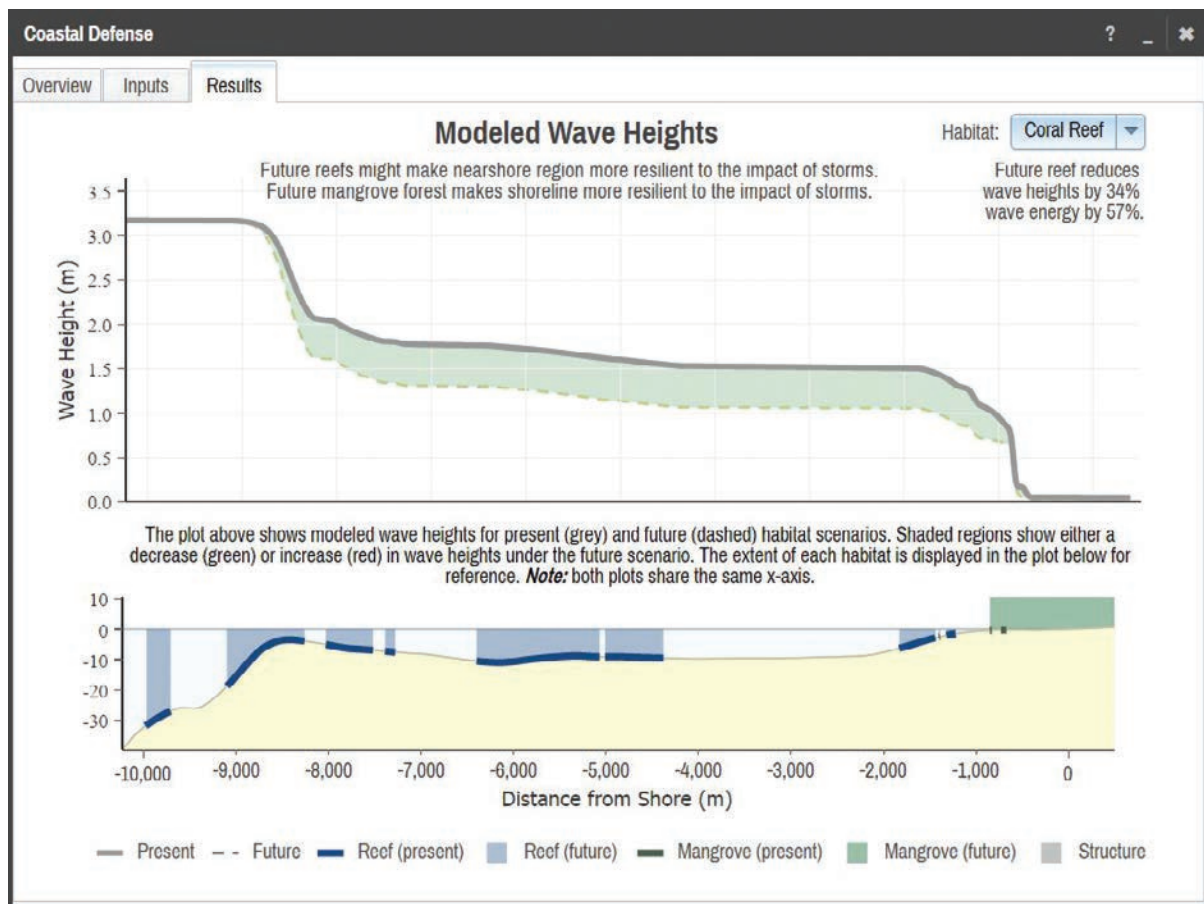


Figure 19.6. The Coastal Defense app output interface shows a simple graph of wave height before and after the habitat scenario, the percentage of overall wave attenuation, and the location of habitats along the one-dimensional profile. Clear language in the upper-right corner of the window states that this combined coral and mangrove restoration scenario can reduce wave heights by as much as 34% and wave energy by up to 57%. Image by The Nature Conservancy © 2015.

Case Studies

Coastal Defense provides reasonable estimates of the beneficial role that coastal habitats play in protecting shorelines. Coastal Defense helps decision-makers understand the role that nature can play in reducing risk and making their communities more resilient. The development of the app is highly stakeholder driven and therefore is versatile and can be applicable to several key audiences. For instance, how waves impact the structural integrity of built infrastructure is of particular concern for the coastal development community. High tides and storm waves can erode and overtop structures, which impacts maintenance costs for communities in the coastal zone and floodplain farmers. Coastal Defense can help managers of coastal infrastructure understand how coastal habitats can reduce wave energy and the risk of structural damage. Likewise, planners and managers are also interested in lowering long-term maintenance costs. They can implement Coastal Defense to prioritize conservation or restoration efforts and determine the sites in which intertidal habitats have the greatest potential to provide wave attenuation benefits to people, shorelines, and infrastructure. And finally, restoration planners can use this app to identify and prioritize conservation or restoration efforts and determine where coastal habitats have the greatest potential to promote not only wave attenuation benefits but also species diversity, fisheries, food security, storm buffering capacity, and long-term ecosystem health.

Puget Sound, Washington

Puget Sound (The Nature Conservancy 2015e) is the second-largest estuary in the country, home to 4.5 million people, and a vital producer for the salmon and shellfish industries. However, these socioeconomic and ecological assets are increasingly vulnerable to rising sea levels, more extreme coastal storms, and more frequent river flooding. Stakeholders in Puget Sound include groups that are often at odds with each other, including tribes and agencies that advocate habitat restoration to recover fish species; the agricultural community, which is focused on maintaining productive farmland; and local towns that would flood daily without a protective levee system. In 2013, the region received significant funding to be invested over the next decade in several projects aimed to restore salmon habitat and improve community protection from storms and floods. To guide these complex investment decisions and identify projects that can provide benefits across the spectrum of stakeholders, communities need information about the performance and cost-effectiveness of implementing either nature-based (green) or built (gray) infrastructure solutions, or a combination of both. This information is readily available for gray infrastructure, but it is more difficult to obtain for natural infrastructure. For example, unlike dikes, which can erode from wave impacts and require regular maintenance, tidal marshes not only interfere with wave passage but also are relatively self-maintaining once fully established and incur little to no long-term maintenance costs. In an effort to address this information gap, TNC partnered with USGS and NatCap to develop the first version of the Coastal Defense app.

Stakeholders in the Skagit Bay estuary in Puget Sound were interested in a decision support tool to help communities meet three objectives: (1) evaluate the role that tidal marshes play in reducing waves that reach levee systems; (2) guide future planning of dike maintenance; and (3) illustrate how their risk might change under different scenarios. In response to these needs, the Skagit Bay version of Coastal Defense allows users to modify the extent of existing marsh habitat under current and future wave conditions to evaluate the change in community risk that may result from either the loss or restoration of protective tidal marshes. Outputs from this app include the estimated changes in wave height and wave energy at the toe of the levee, the probability of the levee overtopping under current and future scenarios, and the amount of additional levee height that is necessary to prevent overtopping.

Coastal Defense is used in Skagit Bay to communicate the value that green infrastructure provides for reducing risk to gray infrastructure and coastal community assets as well as to help illustrate what might happen if marsh loss trends continue. Here, the Coastal Defense app supports the development of win-win projects that provide multiple benefits to stakeholders, from conservationists to farmers in diking districts. Identifying these multibeneficial projects also opens sources of funding that have not been well coordinated in the past. Specifically, stakeholders in the region plan to use this app to guide a coordinated investment strategy that will identify projects that may receive funding for both salmon species recovery and flood risk reduction. To date, this coordinated investment strategy has resulted in millions of dollars in funding for projects at the scale of entire river reaches that were previously rejected when proposed individually.

Mobile Bay, Alabama

TNC and a coalition of partners are restoring coastal Alabama one mile at a time in a project named 100 to 1000: Restore Coastal Alabama (The Nature Conservancy 2015d). The project intends to build 100 mi of oyster reefs that will create the conditions needed to plant, support, and promote more than 1,000 acres of coastal marsh and sea grass. Community-based restoration efforts are enhancing the natural environment of Mobile Bay by providing habitat for oyster larvae to colonize, serving as nursery habitat for fisheries, stabilizing sediments, and dampening wave energy while decreasing coastal erosion. For the past four years, TNC and partners have constructed 10 sites that are actively monitored in Mobile Bay. These projects bring communities together to plan for the future of the bay while deploying 3,295 concrete reef balls, 489 reef blocks, 600 m of cages, 14,000 oyster castles, and 190,000 bags of shell that provide the substrate for future oyster reefs. The sites range in size from 15 m to 1,500 m in length, for a total of approximately 3,600 m, covering just over 2 mi of coastline. In the process of planting structures for oysters to grow on, TNC engaged with 1,500 volunteers who put in over 10,500 hours of labor. This labor does not include contractors who were involved with the larger scale projects at Coffee Island, Alabama Port, and Swift Tract, because those projects were constructed not only for ecosystem but also for economic value.

The location and design of these emerging oyster reefs are determined through stakeholder engagement and developing partnerships, but they are also identified through the use of the Coastal Defense app. The app supports the identification of restorable sites and then models potential future scenarios so that communities can understand the projected coastal protection benefits as oyster reefs, marshes, and seagrass beds grow. This information is vital for getting stakeholder buy-in and makes a stronger case for the permitting of future projects.

The projects that are complete have been monitored for only three years but have already shown some signs of adaptation success. For instance, at Helen Wood Park, marshes have expanded by 7.5% in less than a year without any planting, and submerged aquatic vegetation is rapidly growing behind the reefs. At Swift Tract, another project site, the shoreline behind the newly constructed reefs was more protected from the effects of Hurricane Isaac, while the shoreline to the south with no breakwater suffered the brunt of the increased wave action. This is an ideal example of oyster reef restoration that reduces coastal erosion while housing commercially and recreationally important species over time. In turn, this reef restoration will reduce the risk to human communities that live behind the reefs and marshes while recovering vitally important fisheries for Alabama's economy. No doubt, all the restored oyster reefs will respond and grow in their own way, but through this effort communities are directly addressing the first step of adaptation: building awareness by connecting people with natural adaptation solutions in their own backyards.

Through active and ongoing restoration efforts, TNC and partners are creating viable, nature-based adaptation solutions in Mobile Bay, Alabama (figure 19.7). As recovery continues through the next several decades, this effort will improve conditions in Mobile Bay beyond what they were before the oil spill in 2010. Mobile Bay will be ahead by 100 mi of oyster reef and 1,000-plus acres of marsh and sea grass by physically constructing reefs and promoting the development of coastal habitat. Informed by the Coastal Defense app, the design and implementation of these living shorelines through the 100 to 1000 project has provided critical job creation and community involvement to support and sustain the vision of a better coastal Alabama. In May 2015, the Mobile Bay Coastal Defense app was selected as a finalist in the inaugural Prize for Progress, an award sponsored by the American Society of Adaptation Professionals. This award is given to leading US public, private, nonprofit, and academic organizations that demonstrate how to reduce coastal risk and vulnerability of natural or human systems (The Nature Conservancy 2015a).



Figure 19.7. Nearly 400 volunteers work at Mobile Bay in Alabama to help restore the Gulf of Mexico. Volunteers worked alongside The Nature Conservancy scientists and partners to construct the first quarter-mile of oyster reef as part of the 100 to 1000: Restore Coastal Alabama Project. Photo courtesy of Erika Nortemann, The Nature Conservancy 2011.

Southeast Florida and the Florida Keys

Southeast Florida and the Florida Keys are among the most vulnerable regions in the world when it comes to coastal storms and sea level rise. Fortunately, the region is endowed with natural coastal defenses such as coral reefs, beaches, dunes, and mangrove wetlands that help limit erosion and flooding while also providing wildlife habitat and valuable recreational opportunities for residents and visitors alike.

The previous versions of the Coastal Defense app in Puget Sound and Mobile Bay represent proof-of-concept sites, whereas in South Florida the Coastal Defense app has evolved to an “enterprise” level. Here, the full suite of potential wave model parameters is contained within ArcToolbox, which

is loaded into ArcGIS for Server. This toolbox includes all wind and wave parameters, sea level rise and storms, all coastal habitats, and built infrastructure for exploring green and gray infrastructure solutions. Equipping Coastal Defense with all model parameters has allowed the app development team to customize the interface in South Florida and in the Keys so that users can easily understand the purpose of the app in supporting restoration, adaptation, and conservation decisions.

Coastal erosion and flooding are among Southeast Florida's most pressing concerns. To help address these challenges, the Coastal Defense model was run along the coastline to determine where coral reefs are currently most effective in attenuating nearshore wave energy and therefore protecting shorelines (figure 19.8). This information is now being shared with key stakeholders to identify how conservation and restoration efforts can maximize the ecological and coastal protection benefits that coral reefs provide to communities.

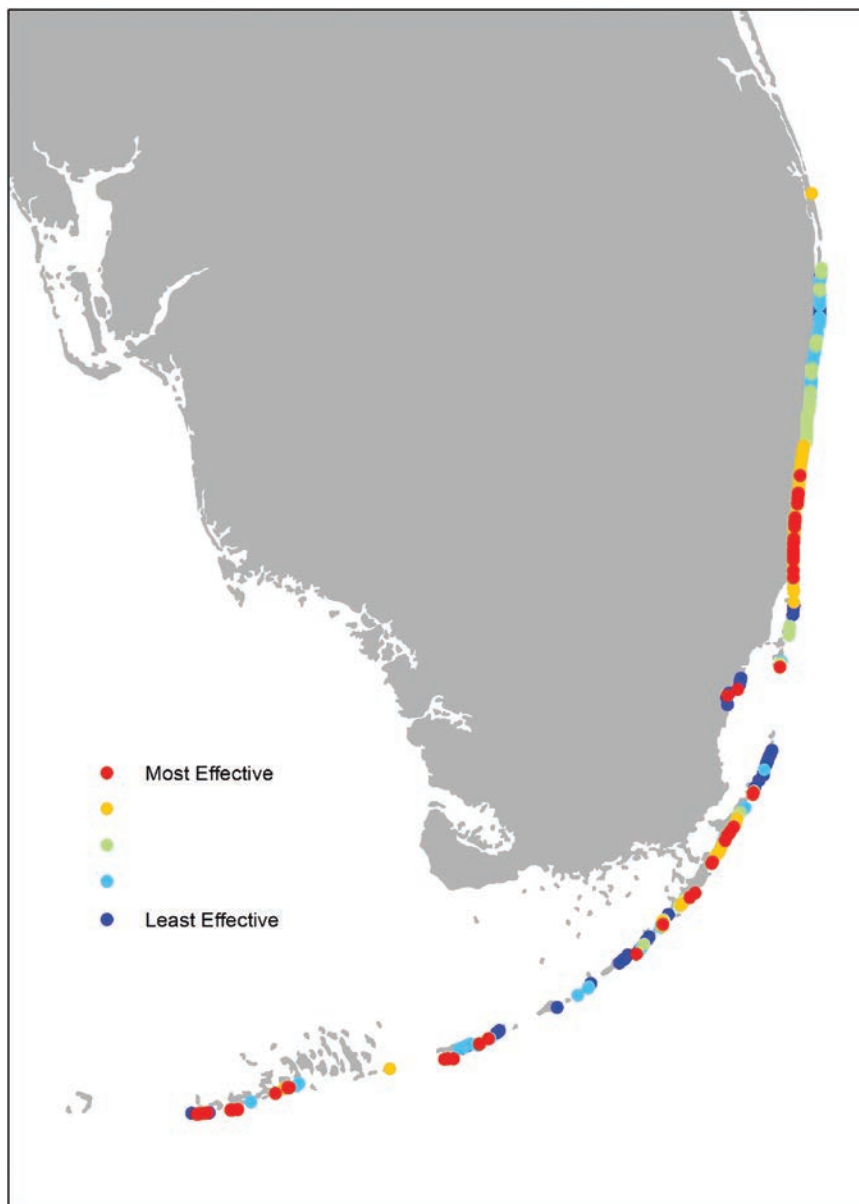


Figure 19.8. This map is compiled from several runs of the Coastal Defense model to help stakeholders visualize the relative protective value that existing coral reefs provide based on the reefs' effectiveness in attenuating nearshore wave height and energy. Image by The Nature Conservancy © 2015.

Other stakeholder priorities in Florida include (1) examining how coral reef restoration might impact protective benefits under different sea level rise scenarios, (2) investigating how coral reefs work in unison with artificial structures to protect the shoreline, and (3) exploring how the presence of mangrove forests also provides coastal protection. To address these needs, the South Florida Coastal Defense app outputs the current and potential future protective value provided by coral reefs and mangroves individually, as well as the cumulative benefits provided by both habitats in combination with engineered structures, such as submerged reef balls. This information helps communicate how active management and reef restoration can improve the resilience of the coastline to the impacts of sea level rise.

More and more communities in Florida are aware of the impacts of sea level rise and storms in the low-lying areas of the Keys and elsewhere. They understand how their precious natural resources support tourism, recreation, and fisheries. TNC is working in partnership with the Southeast Florida Regional Climate Change Compact and others to promote nature-based approaches to coastal protection throughout Southeast Florida and the Florida Keys. These efforts include serving as a clearinghouse for best practices and other technical information and spotlighting successful projects that have already been completed. They also include cataloguing opportunities for new projects using a combination of scientific assessments, online decision support tools such as Coastal Resilience and the Coastal Defense app, and local knowledge. A diverse suite of demonstration projects will be designed to advance the science and social acceptance of nature-based coastal defenses, and champions will be sought for other projects throughout the region.

At the 2014 United Nations Climate Summit in New York, Coastal Defense was announced as the best Professional and Scientific App for Disaster Risk Reduction (United Nations Office for Disaster Risk Reduction 2014). As part of the Global Disaster Resilience App Challenge, participants were challenged to submit apps that addressed the “United Nations 10 Essentials for Making Cities Resilient.” The Southeast Florida Coastal Defense app was highlighted for helping cities adapt to climate change by building on good risk reduction practices, which supports the United Nations Office of Disaster Risk Reduction (UNISDR) Essential 8: “Protect ecosystems and natural buffers to mitigate floods, storm surges, and other hazards to which your city may be vulnerable.”

Conclusion

Starting in 2008, TNC began leading a coalition of partners in New York to pioneer an approach to address coastal hazard risks by working with local and federal partners to make sea level rise, storm surge, socioeconomic assets, community vulnerability, and natural resource data available on the web. Now Coastal Resilience is a global network of projects that uses a decision support system designed to directly address climate change. As more mapping tools come online, Coastal Resilience has found a niche in providing a suite of browser-based apps that not only help communities assess risk but also evaluate nature-based mitigation and adaptation strategies.

An essential piece of the Coastal Resilience equation is ensuring that community stakeholders, decision-makers, and practitioners understand the value of the approach and decision support tool so that they are dedicated to sustaining its use and contributing to its growth over the long term. Thus, investment in a decision support system must be coupled with an investment in its delivery to target audiences. For general audiences, the Coastal Resilience website (coastalresilience.org) provides case studies and stories from practitioners who are using the web mapping tool to apply the Coastal Resilience approach worldwide. To most effectively communicate the Coastal Defense message, the app development team has designed a communication strategy that caters to three targeted audiences.

The first audience comprises the database managers and GIS professionals who are tasked with developing the database or modifying the open source code that runs the app. To address the needs of this group, a technical document walks data managers through the process of preparing input data for the model. Comprehensive documentation and training workshops ensure that database managers understand model requirements and can update the database over time.

The second audience comprises the people who will directly interact with the app interface to explore a habitat's ability to attenuate waves. These users include department managers, municipal planning staff, engineers, contractors, and scientists. To help guide users through the scenario analysis process, TNC has developed an integrated training workshop curriculum. This workshop is led by an experienced Coastal Defense representative who walks users through live demonstrations and use cases of the app. This course is supplemented by interactive simulations, which allow users to click through a predetermined scenario process at their own pace. These simulations are accessible both online and offline, which allows users to practice the workflow on their own and provides an opportunity to continue training in more remote regions where an Internet connection is not always reliable.

Finally, an integral goal of the Coastal Defense app is to ensure that the outputs are simple and discrete and that they can be readily interpreted by nontechnical audiences. This group includes planners and managers who require straightforward outputs that help them easily understand the value of the science and modeling that supports restoration, adaptation, and conservation decisions. Coastal Defense simplifies complex wave model outputs to highlight the benefits of nature-based or hybrid green/gray infrastructure solutions. The app outputs cross-section line graphs that compare wave height and wave power between current and future scenarios so that stakeholders can visualize how a proposed risk reduction solution impacts wave action under various storm or sea level conditions. The graphs are accompanied by a simple message that explains the percentage of wave height and power that was reduced as a result of the proposed habitat or hybrid infrastructure management action.

Coastal Defense is an illustrative app that is focused on communicating a complex socioecological model, making it accessible to both technical and nontechnical audiences. It gives stakeholders the power to make informed decisions to reduce their community's risk. Since its inception in Puget Sound in 2013, Coastal Defense has evolved to an enterprise level, in which the app can be deployed at various spatial scales and customized to expose specific parameters to meet decision support needs. This flexibility encourages stakeholder participation during and after app development to ensure that the end product is useful to ongoing planning efforts. This active community involvement also helps strengthen stakeholder buy-in for on-the-ground projects, permitting, and policy or regulation changes. In this way, Coastal Defense is a means to help change the traditional perception of what defenses can be as well as help make a more compelling case for the role of nature in protecting coastal communities.

Motivated by its success, TNC and partners plan to expand Coastal Defense to include specific bays and estuaries in Virginia, Hawaii, several island nations in the Caribbean, and more sites in the Gulf of Mexico, all designed on the basis of stakeholder engagement and active restoration work implementing nature-based adaptation solutions. For more information on Coastal Resilience or the Coastal Defense app, go to www.CoastalResilience.org (The Nature Conservancy 2015c).

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Supplemental Resources

Dawn J. Wright, ed.; 2016; *Ocean Solutions, Earth Solutions*, second edition; http://dx.doi.org/10.17128/9781589484603_19d

For the digital content that goes with this chapter, explained as follows in this section, go to the book's online resources (esri.com/esripress-resources/ocean-solutions-2e). Some links and QR codes are also provided here.

Try Me Simulations

The Coastal Defense Try Me simulations include a zipped folder of files for downloading the simulation as well as links to online simulations.

- Miami_CoastalDefense_TryMe: zipped folder contains the four files needed to download the interactive e-learning "Try Me" simulation. Users can create a new folder, unzip all four files, and click the .html file to access the simulation locally without the need for Internet access.
- Coastal Defense: Southeast Florida online Try Me, http://media.coastalresilience.org/Miami_CoastalDefense_TryMe/Miami_CoastalDefense_TryMe.htm



- Coastal Defense: Puget Sound online Try Me, http://media.coastalresilience.org/CoastalDefense_tryme/CoastalDefense_tryme.htm



Additional Coastal Defense Resources

Links and QR codes are provided for the following resources:

- Coastal Resilience training page, <http://coastalresilience.org/training>



- Coastal Defense: Miami digital story, <http://coastalresilience.org/miami-coastal-defense-digital-story>



- Coastal Defense: FAQ section of the Coastal Resilience website, <http://coastalresilience.org/our-approach/identify-solutions/coastal-defense>



- Coastal Resilience Network GitHub repository, <https://github.com/coastalresiliencenetwork>



Restore Coastal Alabama Video

The Coastal Defense app is used in Mobile Bay, Alabama, to measure wave attenuation potential of current and proposed oyster reef restorations. This information is being used to support the 100 to 1000: Restore Coastal Alabama Project, which aims to restore 100 mi of oyster reefs and protect 1,000 acres of marsh in coastal Alabama. The video is available in the book's online resources (esri.com/esripress-resources/ocean-solutions-2e).

CHAPTER 20^{New}

Modeling and Mapping Coastal Ecosystem Services to Support Climate Adaptation Planning

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Abstract

To support decision-makers in their efforts to manage coastal resources in a changing climate, the Natural Capital Project and the Stanford University Center for Ocean Solutions are engaging in, informing, and helping shape climate adaptation planning at various scales throughout coastal California. Our team has built collaborations with Sonoma County regional planners and local scientific and policy experts to inform these local climate adaptation decisions that might minimize the economic and social losses associated with climate change. More specifically, to support the Sonoma County planning community in their efforts to update their Local Coastal Program, we have conducted a spatially explicit coastal vulnerability assessment using the InVEST tool and ArcGIS software. The goal of this analysis is to evaluate the role of natural habitats in reducing exposure to rising sea levels and more intense storms. This chapter describes our approach and preliminary findings based on mapping ecosystem services to support climate adaptation planning in Sonoma County, California.

Introduction

Coastal Impacts Associated with Climate Change

Climate change impacts (e.g., rising seas, increased storms, extreme tides) can lead to economic, social, and environmental vulnerabilities that threaten the supply of ecosystem services. The densely populated coastal communities of the United States directly benefit from a broad range of ecosystem services provided by the dynamic coastal zone, especially protection from coastal flooding caused by storms and rising seas (Arkema et al. 2013). Maintaining natural capital (e.g., benefits from nature embodied in

Earth's lands, waters, and biodiversity) to protect and support vibrant coastal communities is critical in the face of intensifying climate change impacts. These communities are faced with a significant challenge—and opportunity—to proactively manage the consequences of a changing climate.

In California, in which the ocean economy is the largest in the nation at approximately \$39 billion annually and a majority of California's large and growing population lives within the coastal zone (Kildow et al. 2014; Pitkin and Meyers 2012; California Department of Finance 2013), climate change is projected to have far-reaching impacts. Rising sea levels and increased storm events caused by a changing climate, coupled with chronic and long-term coastal erosion problems, reduce the resilience of California's coastal communities and put their economies and ecological infrastructure (e.g., freshwater aquifers) at significant risk. California's coastal habitats can reduce the impacts of sea level rise and buffer from storms, providing the ecosystem service of coastal protection. Coastal California represents a great case study site to evaluate the challenges and opportunities in coastal resilience and adaptation planning using natural capital.

Science Context: Ecosystem Services Provided by Coastal Habitats

Ecosystem services are the benefits that are naturally provided by habitats to people such as erosion control, water purification, crop pollination, and timber production. Loss of habitat reduces the ability of nature to provide these valuable ecosystem services. A diversity of habitats fringing the US coastline (e.g., coastal forests, marshes, dunes, seagrass beds) attenuate waves and thus reduce storm-related damage to shorelines from erosion and inundation (Barbier et al. 2011; Shepard et al. 2011). California's coastal habitats (e.g., sea grasses, kelp forests, salt marshes, dunes) are a valuable part of the coastal landscape and may provide significant protection from rising sea levels and increasingly frequent and intense storm events. As coastal development and rising sea levels damage or destroy these habitats, coastlines and the nearby communities and infrastructure become increasingly vulnerable to storms.

An important challenge for decision-makers is to determine the best mitigation and adaptation strategies that not only protect human lives and property but also protect the ability of coastal habitats to provide the ecosystem service of coastal protection into the future. Modeling and mapping of natural capital and the value that ecosystem services provide can support this critical first step to designing and evaluating science-based climate adaptation strategies in coastal California.

Policy Context: Decision Context

Adaptation to climate change is on the rise in scientific and policy agendas (Adger et al. 2007; Moser 2009; Preston et al. 2009; Ekstrom and Moser 2014) and many governments and nongovernment actors at the national, regional, and local levels are developing adaptation plans for response to climate change. Increasing attention to climate change is a step forward, but many barriers to actionable adaptation policies exist. Overcoming these barriers involves incremental policy, planning, and management choices (Ekstrom and Moser 2014). The most often encountered barriers include (1) lack of quality data and planning tools, which inhibit incorporating the ecosystem services in policy contexts; (2) transitioning from broad-scale planning efforts to project-level actions; and (3) modeling complex impacts beyond sea level rise, particularly with respect to increased storm events.

Climate change, and the threat it poses to California's coastal communities, is properly addressed through the state's land-use policy. The California Coastal Act was enacted in 1976 to address land-use and development regulation in the coastal zone. Local governments in the coastal zone must prepare a Local Coastal Program (LCP) that includes a land-use plan, zoning ordinances, and implementation programs for the land-use plans (California Public Resources Code 30500–26; California State Legislature 2014). Local plans can play a key role in enhancing community resilience by guiding how a community prepares for and responds to climate change (Berke and Lyles 2013). Therefore, local plans are the specific policy vehicle through which our team can assist local decision-makers in setting and implementing effective adaptation policies. The California Coastal Commission (CCC) (2013) reviews and approves LCPs as consistent with (and adequate to carry out) Coastal Act policies, after which the local government becomes the lead agency for permitting most coastal development above the mean high tide line, subject to limited CCC appeal authority (California Public Resources Code 30514a–b; California State Legislature 2014).

The 2013 Sea Level Rise Policy Guidance Public Review Draft represents the CCC's recommendations for how local governments can integrate adaptation into LCP amendments and coastal development permits. The draft acknowledges several needs pertaining to ecosystem services information. It recommends that existing LCP policies to protect natural resources be evaluated to determine the extent to which policies already address current and anticipated changes from sea level rise, and suggests that additional policies may be needed to establish adaptive management plans for natural resources that account for sea level rise. It also recommends that updated LCPs should include (1) maps of potential ecosystem change over time with sea level rise and (2) updated land-use designations and zoning to protect land adjacent to environmentally sensitive habitat areas. Moreover, the draft suggests that the expected loss of habitat that will occur with sea level rise be accounted for by updating policies to provide for new or restored coastal habitat. Finally, it calls for the addition of policies that state that the effects of sea level rise be addressed in management plans for coastal habitats. In our Sonoma County case study, we seek to advance the recommendations provided by the CCC in order to incorporate ecosystem services science into the coastal adaptation decision contexts.

The California Coastal Act defines an *environmentally sensitive habitat area (ESHA)* as “any area in which plant or animal life or their habitats are either rare or especially valuable because of their special nature or role in an ecosystem and which could be easily disturbed or degraded by human activities and developments” (California Public Resources Code 30107.5; California State Legislature 2014). The Coastal Act stipulates that ESHAs be “protected against any significant disruption of habitat values, and only uses dependent on those resources shall be allowed within those areas” (California Public Resources Code 30240; California State Legislature 2014). In practice, not all ESHAs are mapped (proactively), resulting in uncertainty as to where ESHAs exist within a given jurisdiction. ESHA determinations are typically made on a case-by-case basis. Although some jurisdictions have mapped where they believe ESHAs exist, the CCC reserves the right to make that determination on pending applications.

Mapping and Modeling Ecosystem Services to Support Coastal Planning

To proactively adapt to a changing climate and incorporate an ecosystem service approach into climate adaptation planning, it is important to quantify, map, and value the goods and services from nature that contribute to coastal protection and other services that sustain and fulfill human life. The Stanford University Center for Ocean Solutions and the Natural Capital Project are working

with several coastal counties in California to answer three key questions: (1) Where are the impacts (e.g., erosion and inundation) from climate hazards (e.g., rising sea levels, increased temperatures, altered wave climates) likely to be the greatest on coastal systems? (2) What are the consequences of climate adaptation planning on natural capital, habitats, and ecosystem services? (3) Which adaptation solutions are most appropriate and cost-effective considering the social, physical, and legal setting? These questions arise from the need of coastal planners and land-use decision-makers to have scientific approaches and tools to make informed specific decisions in coastal adaptation planning. Shaped by the context of coastal planning decisions in California, our ecosystem service approaches and tools such as InVEST (Integrated Valuation of Environmental Services and Tradeoffs) can lead to substantive change by empowering coastal decision-makers to include the best available scientific information in their decision-making processes.

To map and value the goods and services from natural capital, we are using the InVEST software suite. InVEST is a free and open source suite of software models created by the Natural Capital Project (2015) at Stanford University to map and value the goods and services from natural capital. Our interdisciplinary team of scientists and lawyers from the Center for Ocean Solutions and the Natural Capital Project has partnered with coastal decision-makers in jurisdictions across California to use InVEST to identify where coastal habitats play key roles in coastal protection and to include the multiple benefits of natural infrastructure into coastal adaptation planning documents and zoning ordinances. We are doing the following: (1) updating the planning documents to account for modeled sea level rise scenarios; (2) drafting public safety provisions; and (3) testing model ordinance language in real-world planning contexts.

We are currently engaged with four counties along the Central Coast of California, and we will highlight the current ecosystem service mapping of coastal protection in our Sonoma County case study. The goal of our case study is to evaluate the role of natural habitats in reducing exposure to rising sea levels and more damaging storms, and this chapter reflects the initial application of our findings. In our Sonoma County case study, we seek to advance the recommendations provided by the CCC to incorporate ecosystem services science into the coastal adaptation decision contexts.

Case Study: Sonoma County

As a leader in climate mitigation and adaptation planning, Sonoma County has made significant progressive efforts such as the development of a countywide collaborative initiative to reduce greenhouse gas emissions and the creation of a community-focused climate action plan. By working with regions such as Sonoma County and other climate adaptation leaders, we are able to codevelop new solutions that may be transferable to communities that are receptive to, yet potentially less willing or able to, test new solutions.

Sonoma County has received a two-year grant from the California Ocean Protection Council to develop and adopt updated policies in local planning ordinances that conserve and protect coastal resources from future climate change impacts (figure 20.1). This initiative includes working with experts to compile the best available scientific data and an integrated approach to protecting both built and natural infrastructure to support the long-term health and socioeconomic and environmental resiliency of Sonoma County coastal communities.

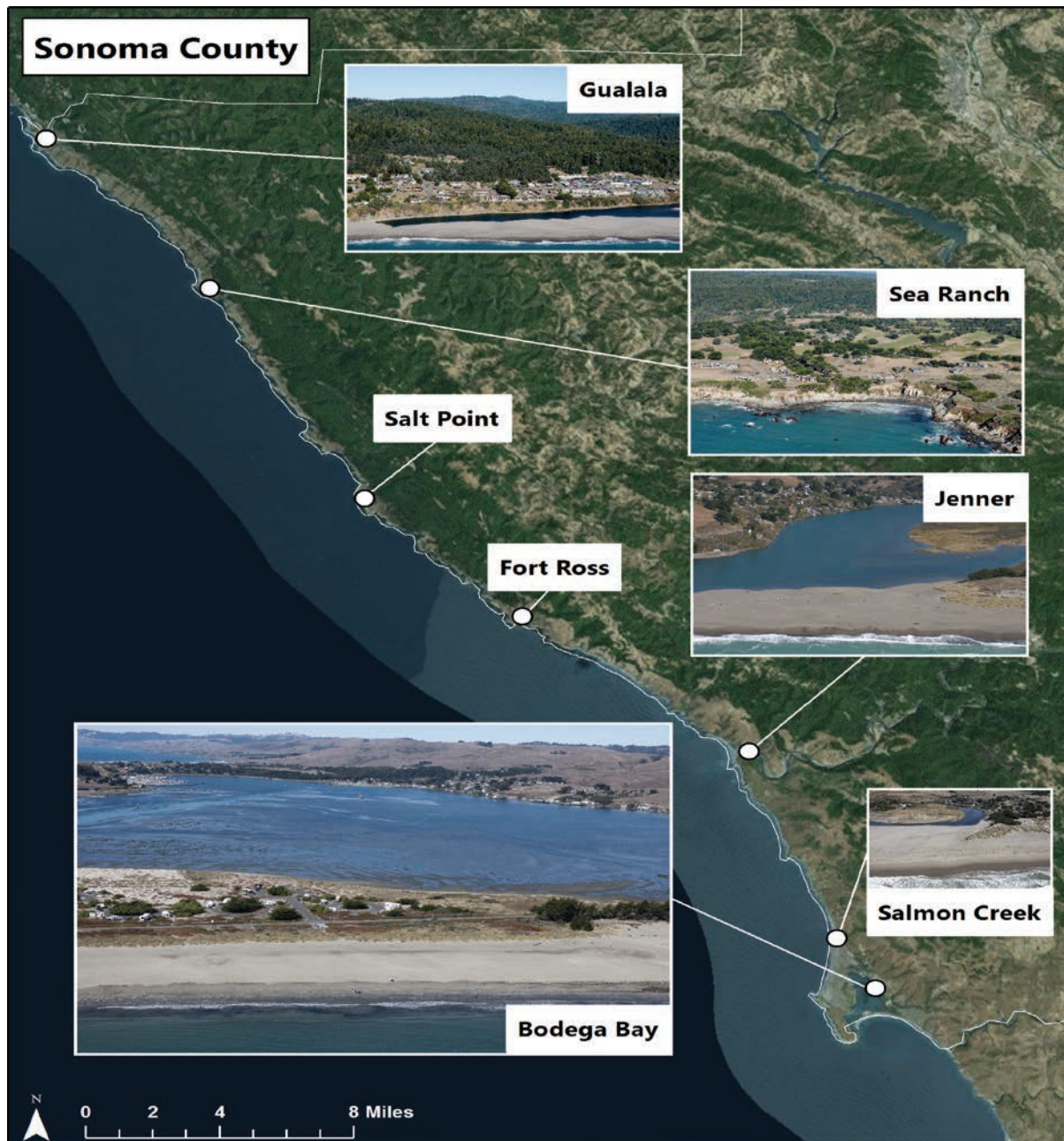


Figure 20.1. Sonoma County coastline. Data sources: Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors. Photos © 2002–14 by Kenneth and Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org.

Our team has built collaborations with Sonoma County regional planners and local scientific and policy experts to inform these local climate adaptation decisions that might minimize the economic and social losses associated with climate change. More specifically, to support the Sonoma County planning community in its efforts to update the Local Coastal Program, the Center for Ocean Solutions, in partnership with the Natural Capital Project, is conducting a spatially explicit coastal vulnerability assessment using the InVEST tool and ArcGIS. The goal of this analysis is to evaluate the role of natural habitats in reducing exposure to rising sea levels and more intense storms.

Geospatial Approach to Ecosystem Service Assessment

Healthy coastal habitats reduce the impacts of storms and shoreline erosion and increase resilience in coastal areas, providing an important ecosystem service. With ever-increasing human pressure on ecosystems, coastal communities require ways to identify locations in which natural habitats provide the greatest benefits so that they can prioritize adaptation planning efforts that protect or restore these critical natural habitats. We used InVEST in combination with ArcGIS to identify areas in which natural coastal habitats provide the most protection from storms and shoreline erosion.

InVEST 3.0.0 is the first version of InVEST with stand-alone versions for a suite of 16 ecosystem service models and analysis tools. InVEST models are spatially explicit, using maps as information sources and producing maps as outputs (figure 20.2). The spatial resolution of analyses can be driven by the scale of available data as well as the scale of the planning question to address questions at the local, regional, or global scales.

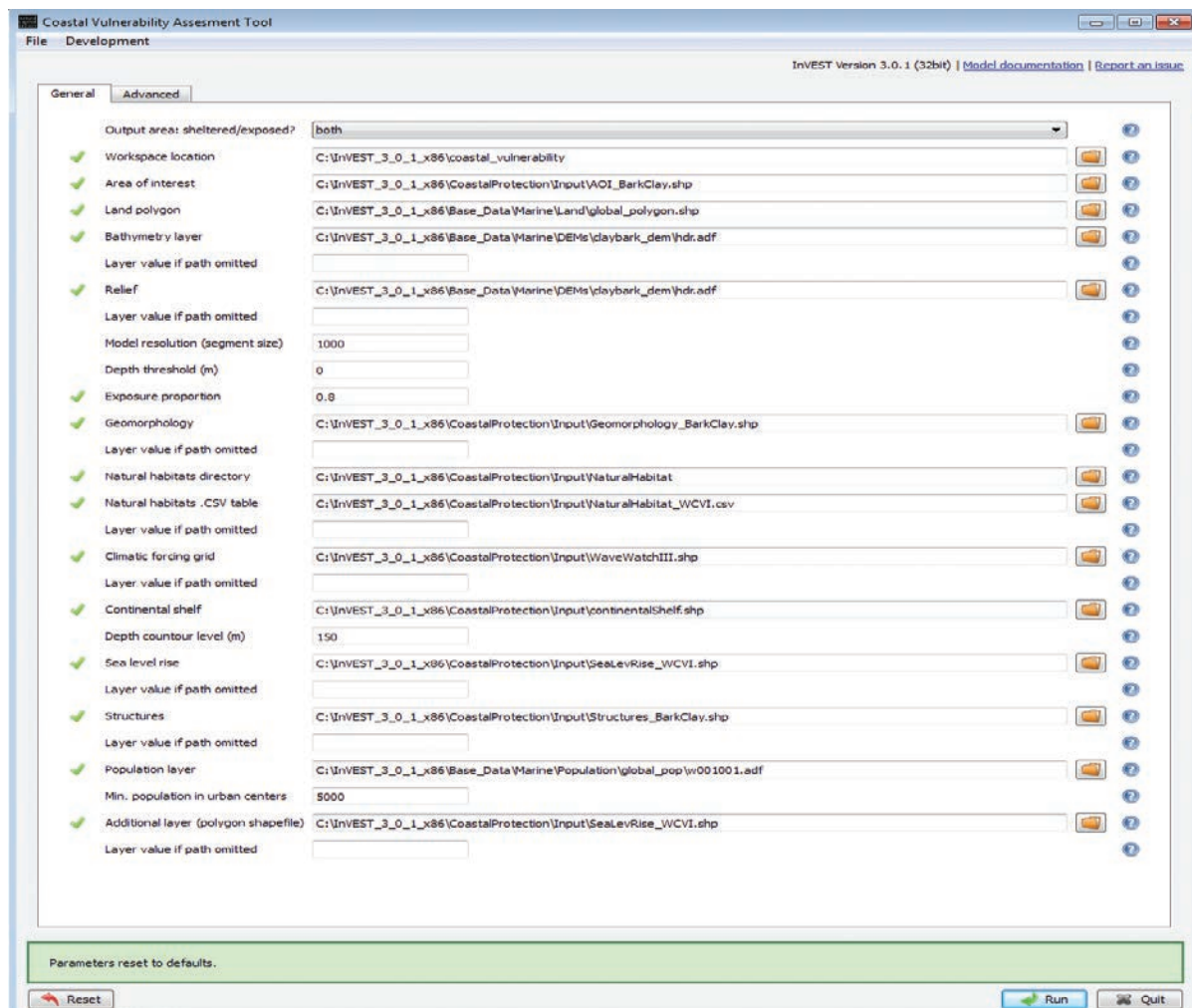


Figure 20.2. Screen capture of InVEST version 3.0.1 Coastal Vulnerability Assessment tool. Courtesy of the Natural Capital Project.

In collaboration with stakeholders, planners can rerun InVEST analyses; and with an iterative process, planners can create new scenarios based on the information revealed by the models until suitable solutions are identified. The ecosystem service models in InVEST are based on production functions that define how an ecosystem's structure and function affect the flows and values of ecosystem services. The models account for both service supply (e.g., natural habitats as buffers for storm waves) and the location and activities of people who benefit from services (e.g., coastal inhabitants and infrastructure potentially affected by coastal storms). InVEST includes models for several different ecosystem services, including nutrient retention, carbon storage and sequestration, renewable energy, and coastal vulnerability.

The InVEST Coastal Vulnerability model incorporates a scenario-based approach to evaluate the role that coastal habitats play in reducing exposure to coastal impacts. The results can be informative to the subsequent evaluation of trade-offs between adaptation strategy approaches and help to inform answers to such questions as the following:

- Where will dune restoration provide the largest protection from climate-related increases in the frequency and severity of coastal storms?
- How will sea level rise affect the ability of marsh habitats to maintain water quality?
- How will seawalls and coastal armoring affect the number of visitors and revenue from coastal recreation?

The InVEST Coastal Vulnerability model produces a qualitative estimate of coastal impact exposure to erosion and inundation during storms. The output is an *exposure index*, which differentiates areas with relatively high or low exposure. Model inputs serve as proxies for various complex shoreline processes that influence exposure to erosion and inundation. By coupling exposure results with population information, the areas along a given coastline where humans are most vulnerable to storm waves and surge can be identified. The most recent InVEST 3.0 version of the model produces exposure layers with and without habitat scenarios so that the user can estimate the role of habitats in reducing exposure.

Preprocessing for the InVEST Coastal Vulnerability Model

The Coastal Vulnerability model data inputs include

- a polyline with attributes about local coastal geomorphology (e.g., beach, dune, cliff) along the shoreline,
- polygons that represent the location of natural habitats (e.g., sea grass, kelp, wetlands),
- rates of projected net sea level change,
- a depth contour that can be used as an indicator for surge level (the default contour is the edge of the continental shelf),
- a digital elevation model (DEM) that represents the topography and the bathymetry of the coastal area,
- a point shapefile that contains values of observed storm wind speed and wave power, and
- a raster that represents global population distribution.

Preprocessing for the InVEST Coastal Vulnerability model involves compiling and formatting each of the input GIS datasets and creating an area of interest polygon shapefile to denote the modeling extent. Wind and wave exposure data is represented in the model using a point shapefile that contains values of observed storm wind speed and wave power across an area of interest (AOI)

using Wave Watch III data provided by the National Oceanic and Atmospheric Administration (NOAA) (NOAA National Weather Service 2015). This global Wave Watch III layer is provided as base data with the InVEST tool download. The model requires that all spatial inputs be projected in World Geodetic System 1984 (WGS84). An important preprocessing step for coastal vulnerability modeling includes the projection of all input datasets to WGS84 to ensure alignment with meters as the linear unit.

The geomorphology and natural habitat are to be prepared using the best available spatial data layers for the AOI. For modeling in the United States, a local coastal geomorphology layer can be characterized using the NOAA environmental sensitivity index (ESI) datasets (NOAA Office of Response and Restoration 2015). This line shapefile input is used to compute the geomorphology ranking (1–5) of each shoreline segment on the basis of input from the InVEST coastal vulnerability guidelines (table 20.1). For example, rocky cliffs (rank = 1) are less prone to erosion and inundation than estuaries (rank = 4) or sandy beaches (rank = 5).

Table 20.1. Coastal Vulnerability Ranking System of Biogeophysical Variables for the InVEST Coastal Vulnerability Model

Variable	Rank				
	Very Low	Low	Moderate	High	Very High
	1	2	3	4	5
Geomorphology	Rocky; high cliffs; fjord; fiard; seawalls	Medium cliff; indented coast, bulkheads, and small seawalls	Low cliff; glacial drift; alluvial plain, revetments, rip-rap walls	Cobble beach; estuary; lagoon; bluff	Barrier beach; sand beach; mud flat; delta
Relief	0–20 percentile	21–40 percentile	41–60 percentile	61–80 percentile	81–100 percentile
Natural Habitats	Coral reef; mangrove; coastal forest	High dune; marsh	Low dune	Sea grass; kelp	No habitat
Sea Level Change	0–20 percentile	21–40 percentile	41–60 percentile	61–80 percentile	81–100 percentile
Wave Exposure	0–20 percentile	21–40 percentile	41–60 percentile	61–80 percentile	81–100 percentile
Surge Potential	0–20 percentile	21–40 percentile	41–60 percentile	61–80 percentile	81–100 percentile

Source: Courtesy of The Natural Capital Project.

In the Sonoma County case study work, we represented natural habitats (e.g., sea grass, kelp, wetlands) based on the California Department of Fish and Wildlife shapefiles created during the Marine Life Protection Act process (figure 20.3) (California Department of Fish and Wildlife 2015). The model uses these input layers to compute a Natural Habitat ranking for each shoreline segment, using the rank values in table 20.1. For example, to evaluate how the exposure of an area changes if high sand dunes are removed or lost, users can change the rank value for high sand dunes from 2 to 5.

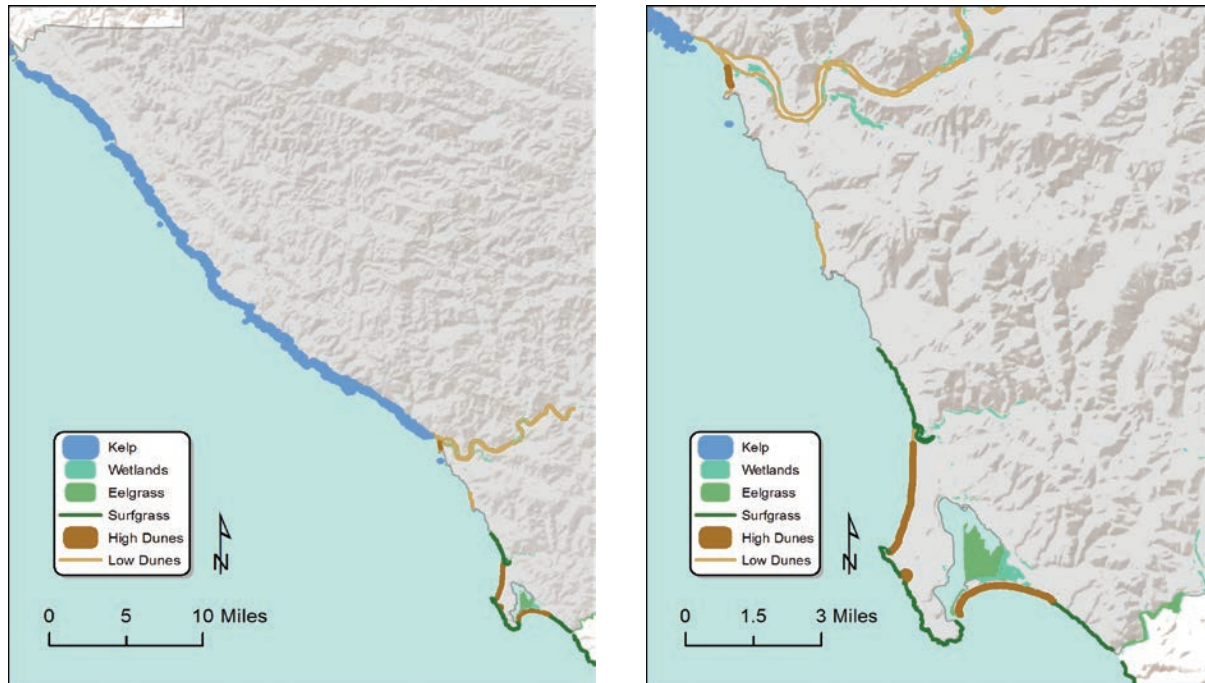


Figure 20.3. Habitat types included in the InVEST model analysis for (left) the full Sonoma County coastline and (right) southern Sonoma County coastline. Courtesy of the Natural Capital Project and the Center for Ocean Solutions.

Surge potential is calculated on the basis of a depth contour that can be used as an indicator for surge level, with the default contour as the edge of the continental shelf. In general, the longer the distance between the coastline and the edge of the continental shelf at a given area during a given storm, the higher the storm surge. A global continental shelf dataset is also included with the InVEST tool download and can be used for modeling unless local conditions (e.g., an island system) require an alternative layer.

A global elevation and bathymetry dataset, Global 2 Arc-Minute Ocean Depth and Land Elevation, also known as ETOPO2 (NOAA National Geophysical Data Center 2001), is provided with the InVEST tool download. Higher resolution DEMs are preferred for local-level modeling if available, as was the case with Sonoma County's Vegetation Mapping and LiDAR Program (Sonoma County Vegetation Mapping and LiDAR Program 2015). Finally, sea level rise projections represented by a polygon shapefile of rates of projected net sea level change for a time horizon are integrated into the model. This shapefile should be created using the best available information

from tide gauges or other sensors for the area of interest. In Sonoma County, we used the sea level rise projections from the National Research Council (2012), which represents the best science for projections by the state of California, including the CCC, the agency with authority over planning decisions in California's coastal zone.

The input data layers produced during the preprocessing stage reveal spatial variation in the variables that come together in the coastal vulnerability model to estimate differences in exposure across the study region. To map exposure under possible futures, these input data layers can be modified to reflect future scenarios of sea level rise, restoration, or conservation of habitats and changes in the intensity and frequency of storms.

InVEST Coastal Vulnerability Modeling

The InVEST Coastal Vulnerability Model produces an exposure index and coastal population raster (table 20.2). The exposure index raster contains ranks of the relative exposure of different coastline segments to erosion and inundation caused by storms within the same coastal region of interest. Ranks vary from very low exposure (rank ~1) to very high exposure (rank ~5) and are computed by taking the n th root of the product of the n variables used in the analysis. Coupled together, the exposure index and coastal population rasters can be used to create maps that show the relative vulnerability of human populations to coastal hazards and sea level rise (figure 20.4). The outputs of the model are a series of raster layers that overlay the shoreline in the coastal region of interest, with a spatial resolution defined by the user (≥ 250 m) (figure 20.5). The spatial resolution of analyses is based on both the scale of available data as well as the scale of the planning question. These rasters contain a number of indexes and rankings of input variables (described as follows) and can be used to create maps that fit the user's needs. The model output creates exposure layers with and without habitat scenarios so that the user can evaluate the role of habitats in reducing exposure.

Table 20.2. Data Outputs of the InVEST Coastal Vulnerability Model

Output Layer Name	Data Type	Description
outputs\run_summary.html	HTML	This file summarizes the run by showing four main pieces of information: <ul style="list-style-type: none"> • A map of the area of interest (AOI), along with the AOI's latitude and longitude • A histogram of the exposure index (between 1 and 5) of the coastal segment • A histogram of the vulnerability of the population living along the coast • A histogram of the vulnerability of the urban centers along the coast
outputs\coastal exposure	Folder	Contains all the layers used to compute the coastal vulnerability index.
1_a_shore_exposure.tif	Raster	Cells that correspond to the shoreline segments are either 0 if sheltered or 1 if exposed.
1_b_geomorphology.tif	Raster	Shore segments are valued from 1 to 5, depending on the geomorphology in the geomorphology layer. Lower coastal values indicate geomorphologic types that are less susceptible to erosion, and vice versa.
1_c_relief.tif	Raster	Shore segments are valued from 1 to 5, depending on the average elevation around that cell. Lower values indicate lower elevations.
1_d_natural_habitats.tif	Raster	Shore segments are valued according to the natural habitats that are present there.
1_e_wave_exposure.tif	Raster	Shore segments are ranked in a similar way to wind exposure but according to their exposure to waves.
1_f_surge_potential.tif	Raster	Segments are ranked according to their exposure to potential surge. First, the exposed segments are assigned a rank in equal proportion between 1 and 5, depending on their distance to the edge of the continental shelf. Then, these values are propagated along the sheltered coast. Isolated coastline segments (such as islands) are assigned the rank of the closest (already ranked) segment.
1_g_sea_level_rise.tif	Raster	Segments ranked in equal proportion between 1 and 5 based on the sea level rise value from the input shapefilea.
1_h_coastal_exposure.tif	Raster	Coastal exposure index computed by equation: $EI = \left(R_{Geomorphology} R_{Relief} R_{Habitats} R_{SLR} R_{WindExposure} R_{WaveExposure} R_{Surge} \right)^{1/7}$

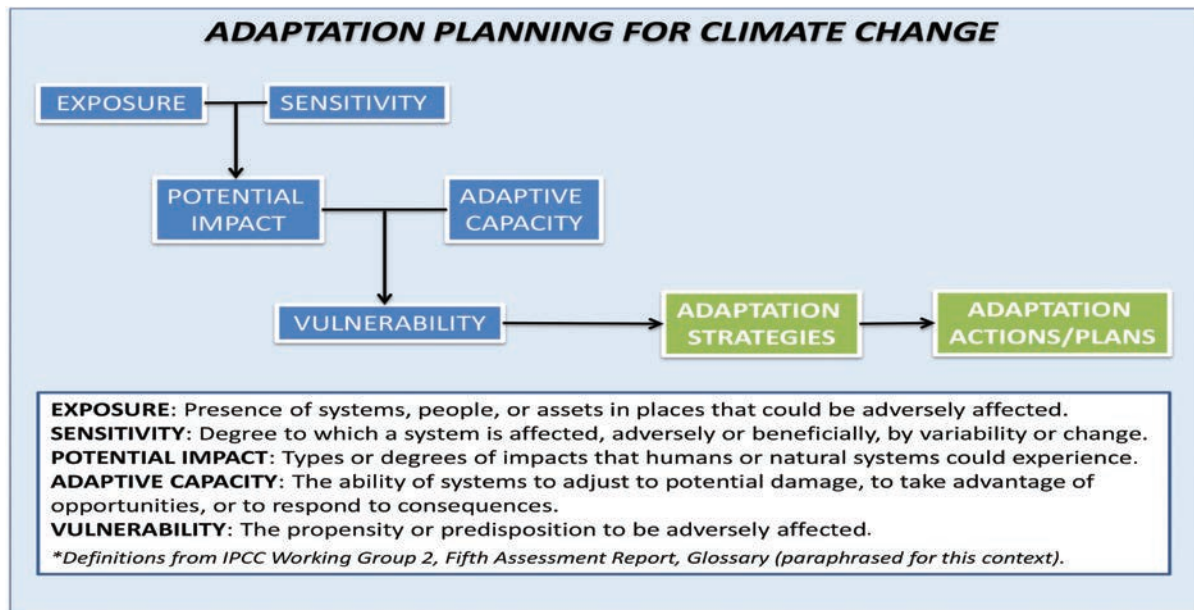


Figure 20.4. Flow diagram of vulnerability and adaptation to climate change adapted from Field and colleagues (2014).

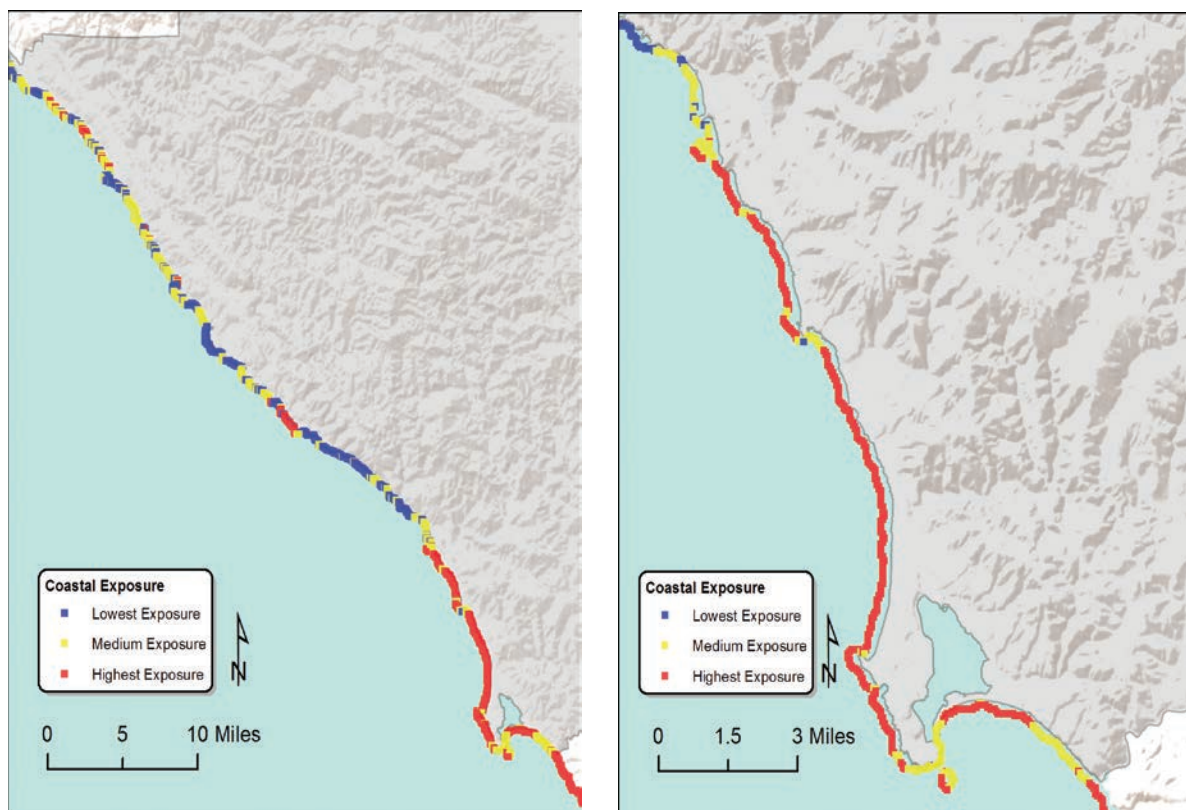


Figure 20.5. InVEST analysis shows relative coastal exposure for 2050 sea level rise scenario on (left) the full Sonoma County coastline and (right) the southern Sonoma County coastline. Courtesy of the Natural Capital Project and the Center for Ocean Solutions.

Based on these limitations and assumptions, the InVEST Coastal Vulnerability tool is an informative approach to investigating relative exposure for a coastline and can be used to identify locations in which coastal habitats play a significant role in reducing exposure to erosion and inundation. However, for local-scale decisions regarding locally specific geomorphic conditions, further site-specific analysis is needed using advanced tools such as the InVEST Nearshore Wave and Erosion model.

Postprocessing for the InVEST Coastal Vulnerability Model

The data outputs from the Coastal Vulnerability model contain all the data layers used to compute the coastal vulnerability index in the form of a comma-separated values (CSV) table. The CSV table contains two columns that are most relevant for visualizing results. The `coastal_ex` column contains results from the coastal exposure analysis, and the `coastal_1` column contains exposure values without the protective service from the habitat layers included in the analysis. With the creation of a feature class, using the WGS84 coordinate system, the results can be spatially visualized along the coastline in many ways; two primary postprocessing methods are discussed as follows.

The coastal exposure values provide a relative ranking of exposure to average wind and wave conditions as well as rising seas (on the basis of values from the InVEST or Federal Emergency Management Agency [FEMA] or NOAA sea level rise input). To visually represent the coastal exposure results, the Symbology tab in the layer properties can be selected for “quantities” and then “graduated colors” for the symbology type. In the field value, `coastal_ex` can be selected and an appropriate point size chosen on the basis of the map and visualization needs. The symbols for the low, moderate, and high coastal exposures are best visualized using the quantile method with three breaks. Through this visualization method, the relatively higher, medium, and lower exposure values are generally represented in red, yellow, and blue, respectively.

The InVEST modeling approach offers an additional value in the ability to modify the results on the basis of a scenario in which the habitats are lost or degraded. To visually represent the role that habitat plays in reducing exposure—thus informing priority locations for preservation and restoration of natural ecosystems (nature-based adaptation strategies)—a similar symbology methodology can be used beginning with key selections. In the feature class attribute table, a float field can be added to the field named `Difference`. The values for the field can be calculated so that each value represents the numerical difference between the `coastal_1` (no habitats) and `coastal_ex` (with habitats) fields, noting that all values in the `Difference` field should be ≥ 0 . After the `Difference` field is populated, all rows can be selected in which the `coastal_ex` values are >3 and in which the `Difference` value is not equal to zero. This selection will represent coastal sections that are relatively highly exposed and in which habitat plays a role in reducing that exposure. In a similar manner, the `Difference` field can be symbolized using a yellow to dark-red color ramp with three quartile breaks. The darker values represent locations in which habitats play a relatively higher role in reducing exposure to coastal hazards (figure 20.6).

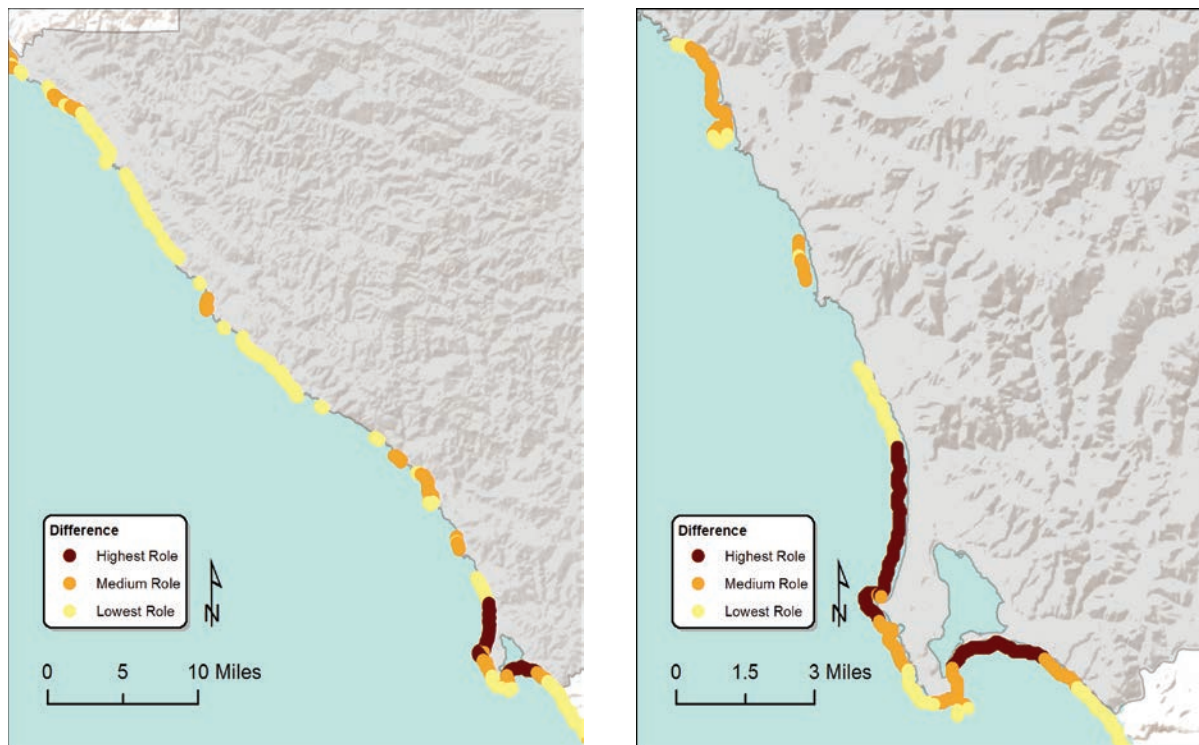


Figure 20.6. Priority locations for natural adaptation, determined by identifying high-exposure locations in which habitats play the largest role in reducing exposure for (left) the full Sonoma County coastline and (right) southern Sonoma County coastline. Courtesy of the Natural Capital Project and the Center for Ocean Solutions.

When overlaid with data on coastal population density, the model's outputs can be used to identify locations in which humans face higher risks of damage from storm waves and surge (Arkema et al. 2013). This model produces a qualitative estimate of such exposure in terms of an exposure index. By coupling these results with population information, the model can show areas along a given coastline in which humans are most vulnerable to storm waves and surge. Additional local information that represents infrastructure, properties, or other assets of interest can be used to identify locations in which higher exposure leads to higher vulnerability (Langridge et al. 2014). Although this approach includes average wave and storm conditions, the model does not take into account coastal processes that are unique to a region, nor does it predict long- or short-term changes in shoreline position or configuration, or fluvial flooding.

InVEST Coastal Vulnerability Model Assumptions and Limitations

One main limitation of this modeling approach is that the dynamic interactions of complex coastal processes that occur in a region are overly simplified into the geometric mean of seven variables and exposure categories. InVEST does not model storm surge or wave field in nearshore regions. More important, the model does not take into account the amount and quality of habitats, and it does not quantify the role of habitats for reducing coastal hazards. Also, the model does not consider any hydrodynamic or sediment transport processes: it has been assumed that regions that belong to the same broad geomorphic exposure class behave in a similar way. In addition, in using this model

we assume that natural habitats provide protection to regions that are protected against erosion independent of their geomorphology classification (i.e., rocky cliffs). This limitation artificially deflates the relative vulnerability of these regions and inflates the relative vulnerability of regions that have a high geomorphic index. Based on these limitations and assumptions, the InVEST Coastal Vulnerability tool is an informative approach to investigate relative exposure of a coastline and identify locations in which coastal habitats play a significant role in reducing exposure. However, for local-scale decisions regarding locally specific geomorphic conditions, further analysis is needed (e.g., the InVEST Nearshore Wave and Erosion model).

Linking Geospatial Science to Climate Adaptation Planning in California

As we have done in our coastal California work, ecosystem service analyses are most effectively used in a decision-making process that starts with stakeholder consultations and continues with iterative discussion that focuses on the stakeholder questions of interest and potential policy options available to the location. Through the iterative development of our work, stakeholders can use InVEST to develop spatial scenarios to evaluate, such as climate adaptation planning alternatives (figure 20.7). The map products created from the InVEST tool support the spatial evaluation of climate adaptation planning alternatives under different sea level rise scenarios and inform how the protective service provided by coastal habitats is likely to change in the future.

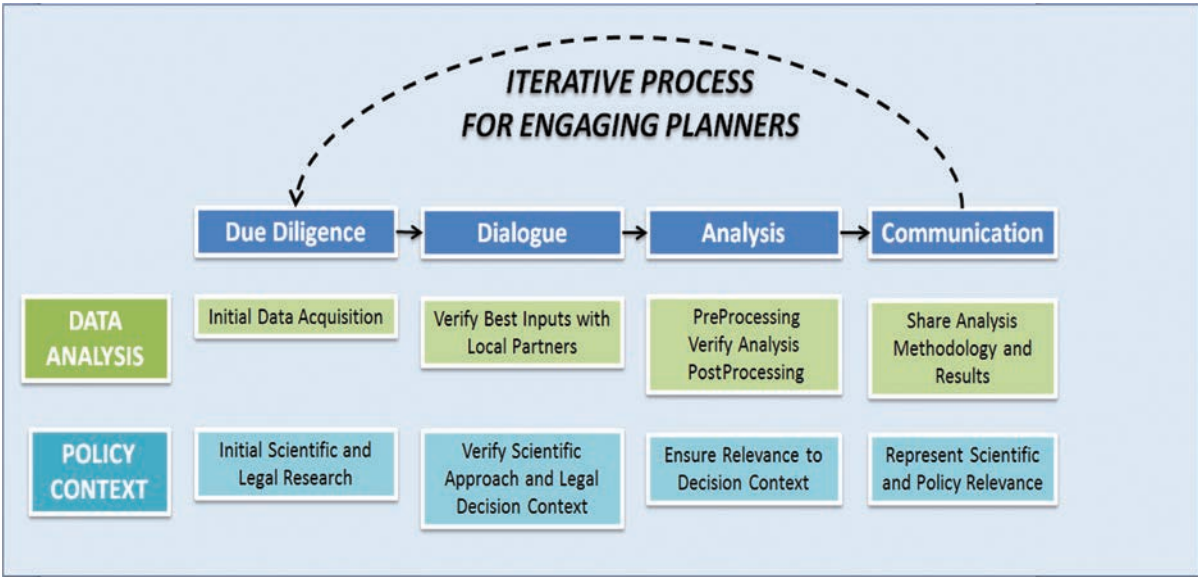


Figure 20.7. Flow diagram of the iterative process used for engaging planners and gaining input on coastal adaptation planning. Courtesy of the Natural Capital Project and the Center for Ocean Solutions.

We are using the outputs to better understand the relative contributions of these different model variables to coastal exposure and highlight the protective services offered by natural habitats to coastal populations. This information can help coastal managers, planners, landowners, and other stakeholders identify regions of greater risk to coastal hazards, which can in turn better inform development strategies and permitting. Results provide a qualitative representation of erosion and inundation risks rather than quantifying shoreline retreat or inundation limits.

Case Study Application of the Coastal Vulnerability Model in Sonoma County

The InVEST Coastal Vulnerability model was applied to investigate where habitats protect against impacts from coastal hazards, and our team is currently engaging stakeholders and policy makers to revise, improve, and translate results to meet their needs for adaptation planning. The science-policy process is iterative in that feedback we elicit from stakeholders improves the model inputs and policy relevance of outputs, and the model results in turn inform future planning discussions and so forth. In Sonoma County, north of the Russian River mouth, the predominant coastal features are kelp forests backed by mostly low coastal terraces and scattered coastal cliffs along the coast. Based on our model results, these kelp forests provide minimal reduction in exposure to erosion and inundation during storms compared with other natural habitat features in the area. The area south of the Russian River is characterized by longer beach expanses, including a two-mile-high dune and two estuaries with wetlands. These types of habitats may significantly reduce exposure to coastal impacts in this region. The spatially explicit valuation of ecosystem services supports the identification of the role of natural habitat in specific locations (e.g., high-dune systems that buffer storm surge in Sonoma County).

The map output of the InVEST model for Sonoma County depicts relative exposure to coastal erosion and inundation across the greater Sonoma County coastal area (see figure 20.5). The results identify areas of highest hazard relative to the rest of the Sonoma County coastline, indicating potential areas or hot spots to prioritize management and further quantitative modeling. The next steps involve the evaluation of any assets of interest (transportation routes such as Highway 1, coastal parks and trails, communities, public infrastructure, and so forth) to determine the relative vulnerability that the assets may experience under 2030, 2050, and 2100 sea level rise projections. To evaluate the benefits of habitat protection, the difference in relative exposure in scenarios with and without habitat were mapped and visualized (see figure 20.6).

In Sonoma County, this map highlights the relative role of habitat (low/moderate/high) in reducing exposure to erosion and inundation during storms in the highest exposure areas. For example, the habitat areas that play the largest role in reducing exposure are located in the high-dune habitat near Doran Beach and south of Salmon Creek.

Results can also help evaluate different climate adaptation strategies, and when overlaid with data on coastal population it helps identify locations in which communities face higher risks of damage from storm waves and surge. The final coastal vulnerability maps we will produce during the next steps of our work will identify where coastal habitats are currently providing protective services to people and property. The maps will depict results from a vulnerability index calculation indicating where natural and human communities are the most exposed to coastal erosion and inundation and which communities are at the greatest risk of loss of other services.

Sonoma Case Study: Adaptive Planning

Sonoma County is at the beginning of a two-year grant process to incorporate the best available science on sea level rise into its local coastal program; and before receiving this grant funding, the county had been working to update its LCP. Because of the long-term nature of planning processes and the sea level rise grant timelines, the current modeling results will require a later amendment to the LCP. Our team of lawyers has worked with Sonoma County to provide countywide policy language for the current LCP update about the modeling work and vulnerability assessments that

are currently under way. This language informs the public about the research on sea level rise that is under way through the grant process and about the optional adaptation strategies that are likely to be implemented in the upcoming LCP amendment. The language ensures that, where possible, our scientific analysis of the role that habitats play in increasing coastal resilience will be integrated into local policy.

Evaluating Adaptation Planning Alternatives

Coastal communities and state agencies use analysis and mapping to employ site-specific strategies (i.e., protect, accommodate, and retreat) in a way that improves overall coastal resilience (Herzog and Hecht 2013). Retreat strategies promote the ability of natural systems (e.g., beaches, dunes, wetlands) to respond to the many impacts of climate change on the nearshore ecosystem and allow these systems to migrate landward, ensuring their survival. In turn, these systems provide cobenefits for coastal communities and mitigate impacts exacerbated by increased coastal erosion and inundation. However, given the state of existing development and infrastructure in the coastal zone, retreat strategies may not be appropriate everywhere (Bell et al. 2014). Planners need a suite of criteria for identifying which strategies, applied in which places, maximize overall resilience. In the next steps of our work, we will be examining the full range of options, from built or “gray infrastructure” to natural or “green infrastructure,” and combinations of the two.

Whether adaptation approaches will be strategic in nature, and whether they will contribute to healthy nearshore ecosystems, depends on communities’ ability to engage in long-term, science-based adaptation planning that places value on maintaining and enhancing ecosystem function and the political will to do so. Coastal communities are responding to sea level rise and damage from increased storm intensity by using gray solutions (e.g., seawalls) and green solutions (e.g., dune or wetland restoration), or a mix of both. Gray solutions are traditional approaches whose design generally does not incorporate coastal habitats. Green solutions, by contrast, consist of nature-based approaches whose design accounts for the role that habitats can play in reducing exposure to sea level rise and associated impacts and in providing additional ecosystem service benefits beyond coastal protection, such as supporting wildlife, coastal tourism, and property values.

To minimize economic and social losses associated with climate change, local, regional, and national governments are developing plans to proactively prepare, respond, and adapt in the future (table 20.3). Whether those approaches will contribute to healthy nearshore ecosystems over time will require political will to embrace approaches that simultaneously yield social, economic, and environmental resilience.

Table 20.3. Coastal Vulnerability Adaptation Strategies

Adaptation Strategy	Definition	Example	Solution
Protection: Hold the line	Defend the location of existing development by armoring the coast with hard armoring (e.g., seawalls, riprap, revetments) or soft armoring (e.g., sand, vegetation).	The Horizontal Levee concept, implemented in San Francisco Bay, uses tidal marshes and smaller inland levees for shoreline management, capitalizing on the capacity of tidal marshes to reduce the height of storm waves (The Nature Conservancy 2014).	Green-gray hybrid
Accommodation: Adjust to the line	Increase development's resilience to climate change and protect coastal ecosystems through the use of traditional zoning, building code, and flood protection code tools (e.g., impact fees, density restrictions, setback buffers).	The New York Aquarium experienced significant flooding damage as a result of Hurricane Sandy. Rebuilding plans call for raising the new shark building several feet higher to meet new flood-zone predictions, moving air intake vents from the flood doors to the roof, moving electrical panels out of basements, and installing full-height storm doors on some glass doors that were only partly protected (Susan A. Chin, personal communication 2015).	Gray
Retreat: Get away from the line	Channel new development out of vulnerable areas while allowing existing development to be relocated, demolished, or inundated by the rising sea.	The Surfers Point Project used a retreat strategy for a beachfront bike path, relocating the erosion-damaged infrastructure inland and restoring natural processes by replacing paved beachfront land with a cobble berm covered by vegetative dunes (The Nature Conservancy 2014).	Green-gray hybrid

Source: Adapted from Herzog and Hecht 2013.

A pitfall of adaptation planning is that some strategies have unintended adverse consequences. *Maladaptation* is a term used to describe an action that is ostensibly taken to avoid or reduce vulnerability to climate change but that inadvertently increases the vulnerability of other systems, sectors, or social groups. In collaboration with local planners and decision-makers, our interdisciplinary team will help counties and cities evaluate adaptation strategies to enhance resilience and avoid maladaptation. To avoid maladaptive practices, communities and state agencies should

answer the following questions regarding project practices to address rising seas (after Barnett and O'Neill 2010):

1. Will the strategy result in a net increase in emissions of greenhouse gases?
2. Will the strategy (and/or its impacts) disproportionately burden the most vulnerable people (lower income, older, minority populations)?
3. Will the strategy reduce incentives to adapt in the future?
4. Will the strategy create “path dependency” (i.e., commit capital and institutions to trajectories that are difficult to change in the future)?
5. Will the strategy result in economic, social, or environmental costs that are high relative to alternatives?

Bridging the Gap

As a boundary organization that is working to bridge the gap between the research community and decision-makers, our team of scientists, analysts, and lawyers is able to (1) advance the science of ecosystem service modeling to support climate adaptation planning, (2) engage local communities in an iterative process to develop a scientifically robust coastal vulnerability assessment for Central Californian counties that enables them to quickly evaluate the relative effectiveness of various adaptation strategies, and (3) translate cutting-edge science into policy that supports the capacity of California counties to engage in sustainable coastal adaptation planning.

Our iterative approach involves partnership with the local counties and collaboration with federal and state agencies (e.g., the CCC, California State Coastal Conservancy, Ocean Protection Council, NOAA Office for Coastal Management). These engagements also provide the opportunity to interact and leverage relevant research with academic and nongovernment institutions (e.g., Sonoma County Agricultural Preservation and Open Space District, The Nature Conservancy, Central Coast Wetlands Group). Our work provides specific and tangible learning opportunities and examples for replication elsewhere by public- and private-sector interests coping with climate adaptation. Our team engages in an iterative process with county decision-makers and local officials to update local coastal planning documents for sea level rise and ensure the development of maximally useful approaches and tools for incorporating climate information into management strategies and project analysis.

Transferability

California's coastal jurisdictions are vastly different because of their different geomorphic characteristics (e.g., beaches, bluffs, estuaries), coastal and nearshore processes (e.g., waves, currents, sediment budgets), and rates of sea level rise. Because of these physical distinctions as well as other factors, including unique cultural and political views, each jurisdiction approaches coastal planning decisions differently. By codeveloping our methods with city- and county-level planners as well as with state-level guidance, we allow for flexibility to tailor information and refine analysis according to the jurisdictional context.

Our work is fundamentally about developing methods and transferable tools to incorporate climate information in the decision-making processes. In particular, we are uniquely positioned

to facilitate the transfer of science, approaches, lessons learned, and tools because we work with four distinct California jurisdictions that comprise a spectrum of infrastructure and economic needs (e.g., tourism, recreation, agriculture, public facilities) as well as diverse geomorphologic and biophysical characteristics (e.g., beaches, wetlands, lagoons, bluffs). Through consistent planning processes such as the LCPs, the California Coastal Act addresses land-use and development regulation in the coastal zone; and jurisdictions must prepare planning documents and zoning ordinances at this land-sea interface. Requests for increased uniformity and transferability of approaches has been noted at the local, county, and state levels. Our work across jurisdictions not only helps these jurisdictions learn from one another but also fosters collaboration with state and federal agencies to inform the transfer of knowledge from these jurisdictions to other jurisdictions in California and beyond.

A similar approach has been applied in other California coastal climate adaptation planning contexts to locate specific natural habitats that can reduce vulnerability to sea level rise and storms (Langridge et. al 2014). Although each coastal jurisdiction is unique in California and uses local planning documents that reflect their social and biophysical attributes, each jurisdiction must adhere to California's overarching legal framework pertaining to sea level rise. By strategically choosing adaptation alternatives, jurisdictions can work to protect people and property while also protecting or restoring dwindling critical habitat and the full suite of benefits that those habitats provide to coastal inhabitants. Sea level rise management and climate adaptation planning require a comprehensive understanding of the interplay between the ecological, legal, social, and political systems in these particular jurisdictions.

Conclusion

The map products created from the InVEST tool support the spatial evaluation of climate adaptation planning alternatives under different sea level rise scenarios and how ecosystem services provided by coastal protection are likely to change in the future. This modeling and mapping approach has allowed our team to visually represent the role that natural habitat plays in reducing coastal exposure in Sonoma County, which will allow us to inform priority locations for nature-based adaptation strategies during the next steps of our collaborative work.

Through the use of the InVEST Coastal Vulnerability tool, our team can provide relevant scientific information in a format that is relevant for climate adaptation planning discussions and ultimately relevant for policy decisions to meet the requirements of the California Coastal Act. Codeveloping our methodology with city- and county-level planners and state-level guidance provide us the flexibility to tailor information and refine analysis according to the jurisdictional context. We will work with Sonoma County to employ a range of project-level strategies (protection, accommodation, and retreat) that are calculated to improve overall resilience through a mixture of gray and green solutions (see table 20.3). Sonoma County will set a precedent in developing community-scale adaptation policies in a way that takes ecosystem service analysis into account. Through the use of the InVEST Coastal Vulnerability tool, our team can provide relevant scientific information in a format that is relevant for climate adaptation planning discussions and ultimately relevant for policy decisions to meet the requirements of the California Coastal Act.

Acknowledgments

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Supplemental Resources

Dawn J. Wright, ed.; 2016; *Ocean Solutions, Earth Solutions*, second edition; http://dx.doi.org/10.17128/9781589484603_20d

For the digital content that goes with this chapter, explained below in this section, go to the following link or QR code. A hyperlink is also available in the book’s online resources (esri.com/esripress-resources/ocean-solutions-2e).

Story Map app

- Incorporating Natural Capital into Climate Adaptation Planning, <http://arcg.is/1Rk7gCb>



This Story Map app explains how incorporating natural capital into climate change adaptation planning can aid coastal planners in making cost-effective, informed decisions that protect both natural habitats and the communities that depend on them. The Story Map focuses on Sonoma County, California, and identifies where natural habitats play the largest relative role in protecting coastal communities from climate change impacts in that region.

CHAPTER 21^{New}

The Tetiaroa Atoll Research Project: Documenting Changes in Island Morphology and Biodiversity through GIS-Based Field Research

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Abstract

The Tetiaroa Atoll Research Project represents a unique opportunity to analyze island geomorphology and biodiversity in a pristine natural laboratory setting. Situated in the middle of the South Pacific Gyre, the Tetiaroa Atoll is part of the Society Islands of French Polynesia (17°00'S, 149°33'W). It is isolated by 50 km from its nearest high-island neighbor, Tahiti. Small enough (about 5 sq km of low-island terrain situated around the 12 sq km lagoon) to lend itself to comprehensive terrestrial and marine biological resource inventories, the atoll is entirely under the private ownership of the Marlon Brando Estate. The University of Redlands, working closely with the Tetiaroa Society (the nonprofit land trust for Tetiaroa), is building a geographic information database for the atoll. The project involves students and faculty in collecting data and performing exploratory research in this unique “natural laboratory.” Research conducted during a May 2014 trip included a bird census, GPS-based shoreline delineation, and kite aerial photography. One motivating factor of the research was the fate of a ground-nesting bird population of the small island of Tahuna Iti. Rats on the neighboring island of Rimatu'u, which is separated from Tahuna Iti by only a narrow, shallow channel, threaten the birds. A preliminary shoreline delineation and kite aerial photography reconnaissance conducted during the 2014 trip, coupled with previous delineation of the atoll completed in 2011, indicate that the centroids of some of the islands have moved as much as 50 m when compared with historical aerial photographs and imagery from 1955, 2002, 2006, 2010, and 2012. Beach erosion on windward slopes and deposition of long sand spits on leeward slopes has occurred, the latter extending as much as 160 m since 1955. The movement of these islets represents a unique opportunity to study and measure changes in island geomorphology. Additional photos, maps, and results from this project are available in the book's online resources. For more information, see “Supplemental Resources” at the end of this chapter.

Introduction

Environmental Setting

Tetiaroa (pronounced “tay-tee-a-row-a”) is an atoll in the Society Islands of French Polynesia. It lies near the center of the South Pacific Gyre (17°00'S, 149°33'W) in the path of the Southeast Trade Winds and almost due south and equidistant from the equator as the Big Island of Hawaii is to the north (figure 21.1). With a total land area of just 5 sq km, it comprises a ring of 12 small, low-relief barrier islands called *motus* that encircle a 12 sq km lagoon. The highest point on Tetiaroa is less than 10 m above sea level.



Figure 21.1. Tetiaroa is an atoll that comprises 12 islets (motus) located in the South Pacific Gyre, 50 km north of Tahiti. Image courtesy of Digital Globe. Data and cartography by University of Redlands, compiled by David Smith.

The University of Redlands, working closely with the Tetiaroa Society (the nonprofit land trust for Tetiaroa), is building a geographic information database for the atoll. The project involves students and faculty in collecting data and performing exploratory research in this unique natural laboratory. Dr. Tim Krantz, professor of environmental studies, has led undergraduate research trips to the atoll in 2003, 2011, and 2014.

Of particular interest to the 2014 trip were the motus Rimatu'u (a rat-infested island) and Tahuna Iti (a nearby predator-free island hosting dense colonies of ground-nesting birds) (see figure 21.1). A 2011 shoreline delineation of the atoll had shown that the channel that separates Rimatu'u and Tahuna was much narrower than it was in 2003, when Dr. Krantz had last visited the atoll. In 2003, the researchers waded a channel approximately 100 m wide and nearly 2 m deep to cross between the two motus. In 2011, the channel was only 20 m wide and less than 1 m deep. Further narrowing of the channel had increased the likelihood of rats being able to cross the channel and destroy the bird colonies. Thus, Dr. Krantz returned to Tetiaroa with a research team to gain a better understanding of how island morphology could be creating the bridge between the two motus. The return trip in 2014 used new methods and tools to study island morphology in relation to the bird population, including further shoreline delineations, channel depth measurements, bird censuses, and kite aerial photography (figure 21.2).



Figure 21.2. Research conducted on motu Tahuna Iti in the southeastern quadrant of the atoll includes kite aerial photography, bird censuses, and shoreline delineations performed on the low-relief islands. Photo courtesy of Ian Eland.

University of Redlands and the Tetiaroa Society

The University of Redlands operates on a semester system that incorporates a May term into its yearly curriculum. May-term field research courses focus intensively on one topic for three weeks, followed by a week for postprocessing, analysis, and archiving of data. For the 2014 May term, Dr. Krantz and spatial instruction manager David Smith selected 11 students from the University of Redlands to participate in an environmental studies course to French Polynesia (figure 21.3). The team's main objective was to learn about Tetiaroa's geomorphology and explore how the atoll's islands may be moving in relation to wave and tidal erosion processes. The course also conducted bird censuses on motu Tahuna Iti, which remains one of the last ground-nesting bird islands in the Society Islands.



Figure 21.3. The University of Redlands 2014 research team at the Tetiaroa Society Ecostation on motu Onetahi. Photo courtesy of Ian Eland.

The Tetiaroa Society (a tax-exempt, 501(c)(3), US nonprofit organization) promotes sustainable practices through education, conservation, and science. Together with the Marlon Brando Estate Trust (which owns the atoll), the Tetiaroa Society is dedicated to preserving the atoll's natural beauty, conserving its resources, and supporting environmental education and research (Tetiaroa Society 2013). Pacific Beachcomber Resorts has partnered with the Brando Estate to build the Brando, a luxury resort situated on motu Onetahi, the only developed island in the atoll. The Tetiaroa Society operates an ecostation on Onetahi that accommodates up to 18 researchers, providing a base station and technical support for research programs on the atoll.

The Brando and other facilities on Onetahi are energy efficient and environmentally sustainable buildings built to Leadership in Energy and Environmental Design (LEED) Platinum construction standards. These facilities provide a base station for scientists to conveniently enjoy Tetiaroa while undertaking their research projects. The University of Redlands is working together with the Tetiaroa Society to build a GIS for the atoll, supporting current and future research programs.

Island Geomorphology

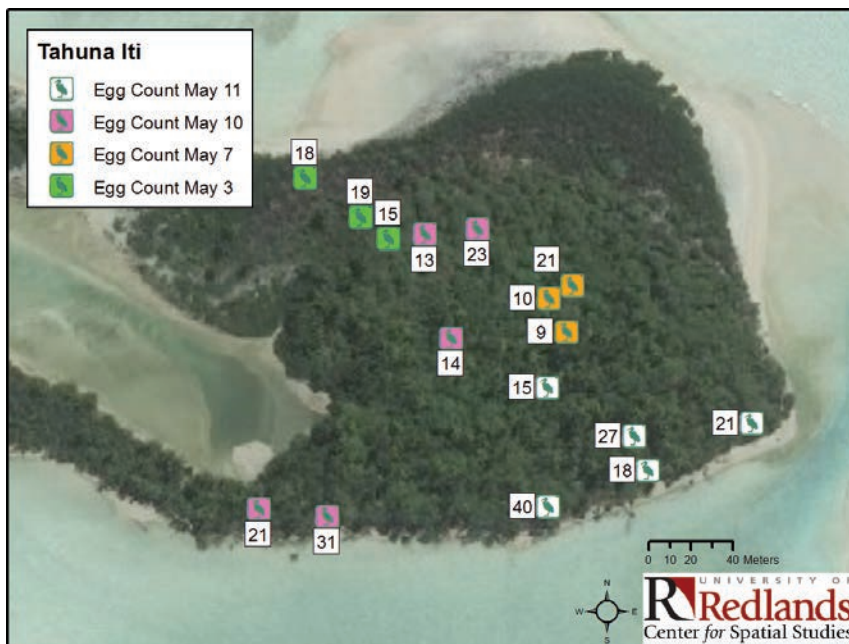
Because of the dynamic geomorphology of Tetiaroa's islands, the researchers had to find stable control points to use as landmarks in aerial and land-based studies. They found these points in coralline stacks distributed across the Tetiaroa lagoon. Calcium carbonate columns that rise from the bottom of the lagoon from depths of as much as 20 m, the stacks have maintained themselves (as the island itself subsides) at just a meter or so below sea level. Using coral stacks as control points, the University of Redlands team geographically referenced aerial photos taken in 1955, 2002, and 2006

to one another. The georeferencing analysis supported the researchers' hypothesis that the coralline stacks are stable: the locations of the stacks have remained the same relative to each other in the 51 years between the images.

The coral stacks tell the classic story of volcanic tropical island geomorphology, with the submergence of the volcano massif as it becomes inactive and moves away from its "hot spot" by means of plate tectonics. In this case, the Pacific Plate is moving southeast to northwest from its spreading center along the East Pacific Rise, at a rate of 102 mm/yr (DeMets et al. 1990). As the massif subsides, what was initially the fringing reef around a high island now maintains itself as a ring of islands around a central lagoon (an "atoll") through bio-accretion of calcium carbonate by the coral reef organisms themselves. Thus, the reef itself maintains the ring of islands that make up the Tetiaroa atoll. Radioisotopic chronologies for coral reefs on Tahiti indicate a subsidence rate of between 0.25 and 0.39 m per 1,000 years (Thomas et al. 2012). In the case of Tetiaroa, the volcanic cone has submerged completely below sea level, leaving just the ring of motus that form the atoll. Within the lagoon on Tetiaroa is a 30 m depression ringed with coral stacks, perhaps the vestiges of the original volcanic crater.

Bird Census

Motivated by the 2011 observation that the channel that separates rat-infested Rimatu'u from Tahuna Iti was narrowing, the researchers used fixed-radius point counts (Dawson 1981; Ralph 1981; Ralph et al. 1995) to estimate the number of eggs laid by the birds on Tahuna Iti (figure 21.4). The goal was to generate a baseline for future research. Sixteen sample points were nonrandomly selected and then georeferenced with a Trimble GPS unit. Then markers were placed at each of the four cardinal points (north, east, west, and south), at 5 m from each georeferenced center point. Eggs and juvenile birds were meticulously counted in each of the four quadrants, and the data was recorded in field logs.



Brushy areas complicated the census because the heavy canopy cover disrupted GPS signals, making the georeferencing of sample center points difficult. A Trimble-Zypher GPS receiver attached to the top of a pole helped enhance reception from multiple GPS satellites. The majority of the brush in the northwest of the island had healthy thick vegetation with significant amounts of a parasitic vine (*Cassytha filiformis*). The eggs, however, were mainly in areas with less dense brush, including dead plants that provide light coverage. Ground-nesting birds appeared to prefer *Pemphiliis* and *Portulacca* spp. for their nesting habitat. The highest egg counts were in the southeastern portion of the motu, which was subject to the most wind and sea erosion. Many eggs were on the sands of the beach, mere feet from the shoreline. The southeast shoreline also had the highest nesting count (40 nests with 16 eggs in one southeast quadrant).

The birds identified on motu Tahuna Iti included the Brown Noddy (*Anous stolidus*), Black Noddy (*A. minutus*), sooty tern (*Onychoprion fuscatus*), frigate birds (*Fregata spp.*), and the crested tern (*Thalasseus bergii*). Specifically, the ground-nesting birds were the Brown Noddy, Red-Footed Booby, and Black Noddy.

The research team also looked for signs of predation such as decapitated or dismembered birds. Because the last visit to Motu Tahuna Iti was three years earlier, the team was unsure whether rats had traversed the sand spits and already posed a risk to the ground-nesting bird population. The team found no signs of predation.

Because of the lack of predation on the motu, the ground-nesting birds were not startled or frightened as the team counted eggs. The birds also did not defend their young. The team concluded that the birds had not been exposed to selection pressure, which would promote defensive behavior. The team also concluded that if rats from neighboring motu Rimatu'u crossed one of the sand spits extending from motu Tahuna Iti, they would quickly decimate the ground-nesting bird population. As wind and sea erosion continues to push sediments from the southeast side of motu Tahuna Iti to the northwest sand spits, the gap between Tahuna Iti and Rimatu'u is likely to close, putting the ground-nesting bird population at increasing risk from predation.

Motu Shoreline Delineation

In May 2011, a team of student researchers from the University of Redlands visited Tetiaroa and completed a thorough shoreline delineation of all 12 motus that comprise the atoll. The team recorded shoreline feature characteristics (such as aragonite, coralline rubble, sand, and vegetation) for each motu (figure 21.5). Shoreline delineation data indicates that sand was the most prevalent shoreline feature type, comprising 36% of the total shorelines (table 21.1).

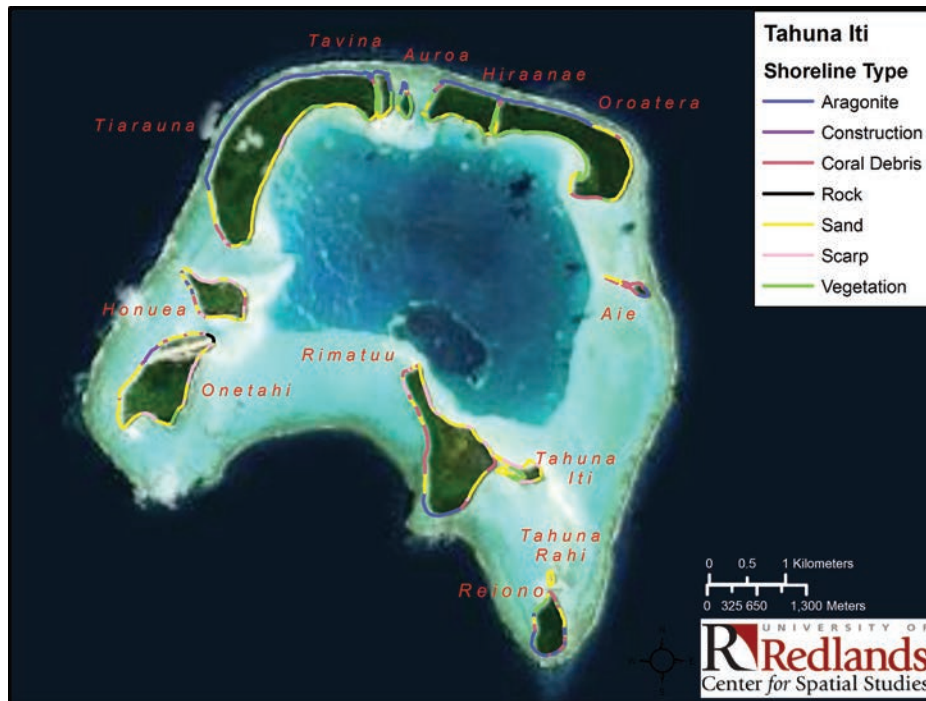


Figure 21.5. All 12 motu delineations in 2011 involve recording data on shoreline features such as aragonite, sand, or vegetation. Image courtesy of Digital Globe. Data and cartography by University of Redlands, compiled by David Smith.

Table 21.1. 2011 Motu Delineations by Shoreline Type

Shoreline Type	Length of Shoreline Type (m)	Amount of Shoreline
Aragonite	8,434.3	22.8%
Construction	314.1	<1.0%
Coral debris	4,345.3	11.8%
Rock	161.3	<1.0%
Sand	13,347.6	36.1%
Scarp	3,148.8	8.5%
Vegetation	7,196.9	19.5%

The four largest motus (Tiaruana, Rimatu'u, Oroatera, and Onetahi) comprise nearly 80% of the land area of Tetiaroa (table 21.2). Tahuna Iti, at 1.4% of the land area, is relatively small. During the 10 days of fieldwork conducted in 2011, students recorded over 36 km of shoreline. Photographs taken in conjunction with the shoreline delineation provide a visual record of shoreline features.

Table 21.2. The Relative Areas and Shoreline Lengths for the 12 Motus That Make Up Tetiaroa Atoll

Motu	Area (ha)	Percentage of Area	Shoreline (m)	Percentage of Shoreline
Aie	2.3	<1.0%	688.1	1.9%
Auroa	4.7	<1.0%	1,030.5	2.9%
Hiraanae	35.3	6.6%	3,237.8	9.0%
Honuea	29.7	5.6%	2,423.5	6.7%
Onetahi	75.1	14.0%	3,983.8	11.0%
Oroatera	87.0	16.3%	5,835.2	16.1%
Reiono	23.2	4.3%	2,004.0	5.5%
Rimatu'u	90.4	16.9%	4,992.1	13.8%
Tahuna Iti	7.6	1.4%	2,384.5	6.6%
Tahuna Rahi	0.9	<1.0%	426.9	1.2%
Tavina	8.0	1.5%	1,530.3	4.2%
Tiaruana	170.9	31.9%	7,650.2	21.1%
Totals	535.1	~100%	36,186.8	100%

Kite Aerial Photography

In May 2014, a second research project completed work on Tetiaroa. The team focused on the Rimatu'u–Tahuna Iti shorelines, updating the shoreline delineations from 2011 and incorporating kite aerial photography (KAP) to create a high-resolution, composite aerial photograph of the islands (figure 21.6). A seamless orthophoto can be useful as a baseline for future visits to the atoll. The KAP project used a Pentax Optio WG-2 GPS camera suspended in a cradle from the line running to a 2.7 m diameter delta kite. At the beginning of each flight, the camera was set to capture images every 10 seconds. Line was released from the spool at two different lengths to conduct high aerial reconnaissance (106.7 m of line released) and low aerial reconnaissance (16.25 m of line released). Ground control points were established during the KAP by a team of students who ran ahead of the kite flight line and positioned the kite stuff sacks as an aerial survey cross, obtaining the geographic coordinates of the center of each cross using a Trimble GeoXH 6000 GPS data logger. Postprocessing of the GPS data through a base station in Papeete (the capital of French Polynesia) revealed horizontal accuracy on the locations of these markers to be consistently below 50 cm.



Figure 21.6. The 2014 KAP project used a Pentax Optio WG-2 GPS camera mounted on a 9 ft diameter delta kite with ground control points (GPS) identified using a Trimble GeoXH 6000. High-flight photos were taken at 107 m, and low-flight photos were taken at 54 m with resolution sufficient to capture bird nests on the ground. Photo courtesy of Ian Eland.

The steady Southeast Trade Winds provided nearly constant southeasterly winds, creating excellent conditions for the kite. The northwesterly shoreline could not be photographed adequately because the kite was typically carried offshore and away from Tahuna Iti by the prevailing winds. A subsequent KAP data collection effort may fill this gap in the aerial photograph coverage by flying the kite from a transect along the interior of the small embayment that runs through the middle east–west axis of the island.

Kite Aerial Image Processing

The team returned with nearly 3,000 digital photos taken from the kite rig on six separate passes (figure 21.7). With a resolution of 3 to 5 megapixels each (approximately 6.8 mm per pixel on the ground), the KAP images showed the shoreline, vegetation, birds, nests, and even eggs in detail. The camera deployed on the kite had an internal GPS that added geographic coordinates to the image metadata, which aided georeferencing of the data.

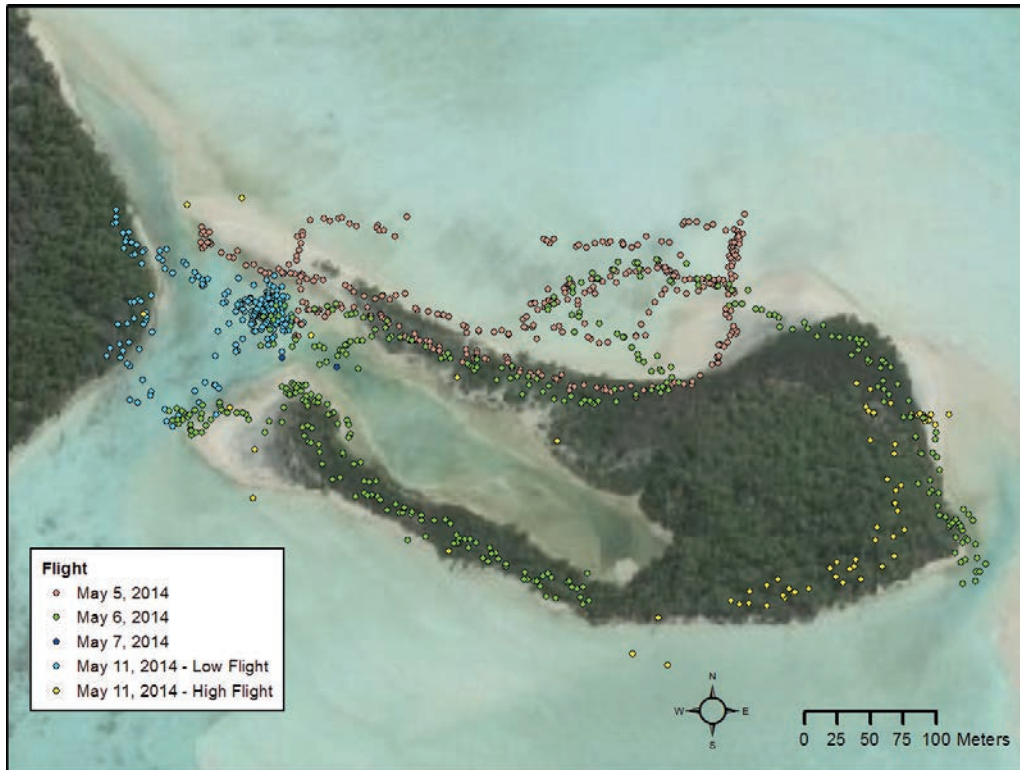


Figure 21.7. The GPS coordinates of the camera taking the images. Over 3,000 kite aerial photos were taken during KAP. The number was reduced to 1,102 selected images that cover the entire shoreline. Basemap courtesy of Esri. Image courtesy of Nate Strout.

After returning to California with the KAP data, the team experimented with different methods for creating a seamless georeferenced mosaic, including manipulating the images with the basic shifting, rotating, and skewing tools in Adobe Photoshop and manually aligning the photos to a geographic coordinate system with the georeferencing tools in Esri ArcMap software. Without a high-quality orthophoto or other geographic base layers to use for reference, the team was limited to the ground control points in the images and to the shoreline delineation data discussed previously in this chapter. Ground control points were used only in the low-flight KAP and not set up in a closely spaced pattern. Thus, the control points established by the research team were not present in most of the low-flight images and were not present at all in the high-flight images. Accordingly, natural control points such as trees and debris that were discernable in the images also had to be included in the analysis. The georeferencing tools in ArcMap helped to further warp the photos to reduce the distortion caused by the inconsistent camera angles and altitudes. Using such manual strategies, the team was able to generate semicontinuous high-resolution mosaics covering most of motu Tahuna Iti (figure 21.8).

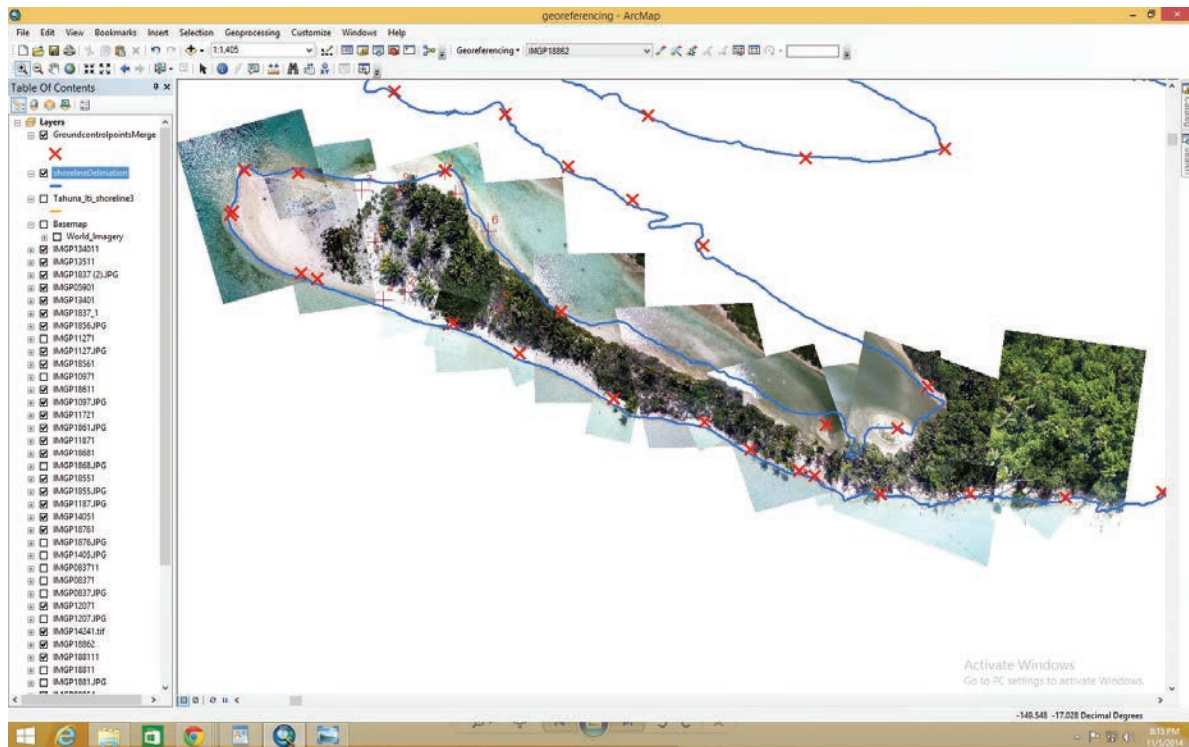


Figure 21.8. The georeferencing tool in ArcMap creates an almost seamless orthophoto. The inconsistent camera angle creates distortion of the images resulting in the orthophoto not aligning with the 2014 motu delineation. Image courtesy of Nate Strout.

The team also evaluated automated and semiautomated solutions for generating photomosaics, including the Photoshop Photomerge tools and Microsoft Image Composite Editor. These toolsets generally use a Scale Invariant Feature Transform (SIFT) algorithm to detect and identify objects in photos and match them based on these objects (Sinha 2015). As the name implies, the algorithm can handle photos at different scales and rotation (as the kite moves up and down), which makes it ideal for postprocessing of photos from kites and other unmanned aerial vehicles (UAVs). The KAP photomosaics created with the SIFT algorithm for this project were sufficient for the exploratory nature of the project. In future stages of the research, planimetric accuracy will become more important; and camera angle, radial lens, and terrain relief distortion will require correction.

Two factors made applying the SIFT algorithm less effective: first, when used in photo stitching, the SIFT algorithm works best with a 20% to 40% overlap between photos, which was not always achieved with the Tetiaroa KAP. To increase the amount of overlap among the KAP images, future studies should try the following strategies: (1) walk at a slower pace for a given capture rate (the 2014 researchers set the camera to capture images every 10 seconds); (2) increase the rate at which photos are captured; and (3) fly the kite slightly higher to incorporate a larger field of view. The fluid nature of the sandy beach, clear water, and lush vegetation of the atoll provided few stable and easily identifiable objects that the algorithm could match across images. Second, motion was also a problem. Waves, fish, birds, shadow from clouds, and vegetation blown by wind all moved as images were captured from the kite.

To compensate for these factors, the team experimented with two software programs that use additional matching algorithms to create two-dimensional photomosaics and three-dimensional digital surface models (DSMs): a free open source toolkit named VisualSFM and a commercial software named Photoscan marketed by Agisoft (figure 21.9). The two systems use different

algorithms, along with a bundle-adjustment algorithm to provide higher alignment quality, solve intrinsic and extrinsic camera orientation parameters, and create a dense surface reconstruction and texture mapping to produce photo-realistic three-dimensional (3D) models (Semyonov 2011). These programs are applied in numerous UAV projects (and, to a lesser extent, with KAP) to produce photo-realistic 3D models for crop health monitoring, construction site surveys, watershed management, and other applications. Although a planimetric model of the atoll can be useful in research efforts, a photo-realistic 3D model was deemed sufficient for this exploratory research project.

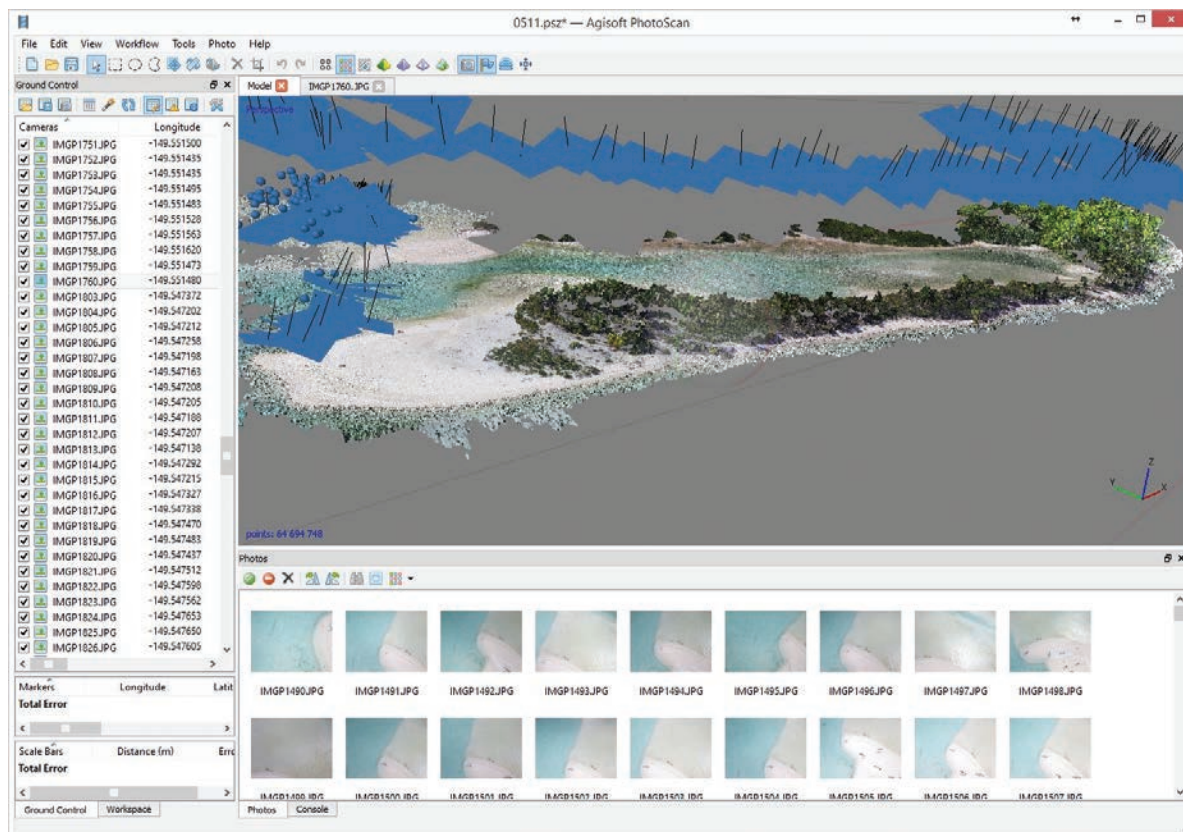


Figure 21.9. Dense-point cloud 3D reconstruction with Agisoft Photoscan software. Image courtesy of Nate Strout.

By experimenting with parameters and manually defining control points, the team created photomosaics and DSMs of the island (figure 21.10). To date, the team has not successfully created a seamless orthophoto coverage of the entire island. Areas that lack distinguishable features, such as the sand flats at the northwestern tips of the motu, were difficult to convert into photomosaics for reasons stated earlier. The team will continue to work with the KAP imagery with the goal of creating a seamless orthophoto that can serve as a baseline for future visits.



Figure 21.10. Final orthophoto of May 2014 “High Flight” created through Photoscan by Agisoft.

Image courtesy of Nate Strout.

The team also used the Microsoft Photosynth platform to create an interactive video of the KAP flights that has proven to be an effective and compelling tool when presenting the project and describing the environment of the island. Photosynth is a cloud-based platform for producing “immersive 3D experiences” (Microsoft Research 2015). The team used a new Tech Preview of Photosynth, which includes a variety of “synths” based on how the photos were collected and the type of product the user wants to create. The system is a “black box,” and thus Microsoft does not provide details on the algorithm. All the processing is performed on a Microsoft server, making it simple for end users to create interactive visual products. This cloud-based tool allows a user to upload a series of photos to a website, and then Photosynth processes the data to create the product. The team used the “walk” synth type and, to ensure the maximum coverage and amount of overlap in the photos, used photos from a higher altitude flight conducted May 11, 2014. The resulting synth provided a realistic interactive virtual flyover that allows the user to stop the motion at any point, and zoom and pan (figure 21.11). You can explore the Synth online via Strout (2015).

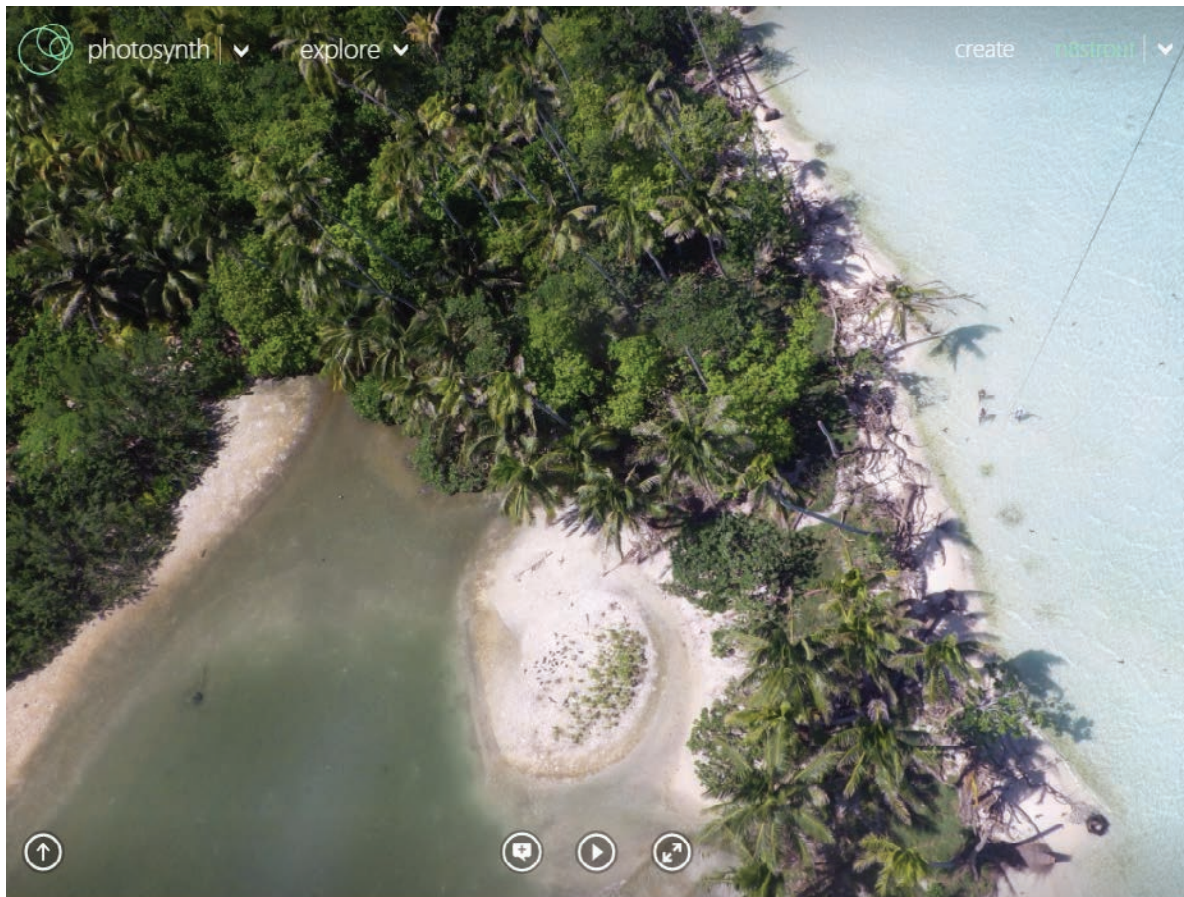


Figure 21.11. The web-based Photosynth tool creates a virtual flyover of Tahuna Iti. Image courtesy of Nate Strout.

Discussion: Motu Movement Analysis and Delineations

An examination of aerial photography from 2010 and 2014 compared with shoreline delineations from 2011 and 2014 illustrates the dynamic environment in which the motus exist. The 2011 shoreline delineation indicates that the small windward islands of the atoll are being eroded on their windward shores from the southeast. The sediments then move by longshore sediment transport of waves to their leeward shores.

Comparing an aerial photograph of Tahuna Iti taken in 2010 with the shoreline delineation conducted in 2011 shows how quickly motu shorelines can change (figure 21.12). Notice the sand spit on the northwest side of Tahuna Iti that extends toward the northwestern neighboring motu, Rimatu'u. The channel that separates the two motus fluctuates yearly and has been gradually thinning over time. The immediate threat to the ground-nesting bird population on Tahuna Iti is the narrow channel that separates the bird island from Rimatu'u, a motu infested with rats. If rats bridge the elongating sand spits, they will quickly invade and consume the defenseless birds.



Figure 21.12. Aerial imagery from 2010, with a 2011 shoreline delineation. Image courtesy of Digital Globe. Data and cartography by University of Redlands, compiled by David Smith.

An aerial photograph from 2012 compared with the 2014 delineation illustrates some significant changes from the 2010–11 analysis (figure 21.13). The 2012 aerial photograph overlain with the 2011 motu delineation (orange) and the 2014 delineation (blue) (see figure 20.13) shows clear indications of erosion on the southern shoreline. Prevailing winds and ocean currents continue to strike the southern shoreline, displacing sediment on the northern side of the motu. The most observable phenomenon in this image is the separation between the 2011 and 2014 delineation on the southern shoreline.

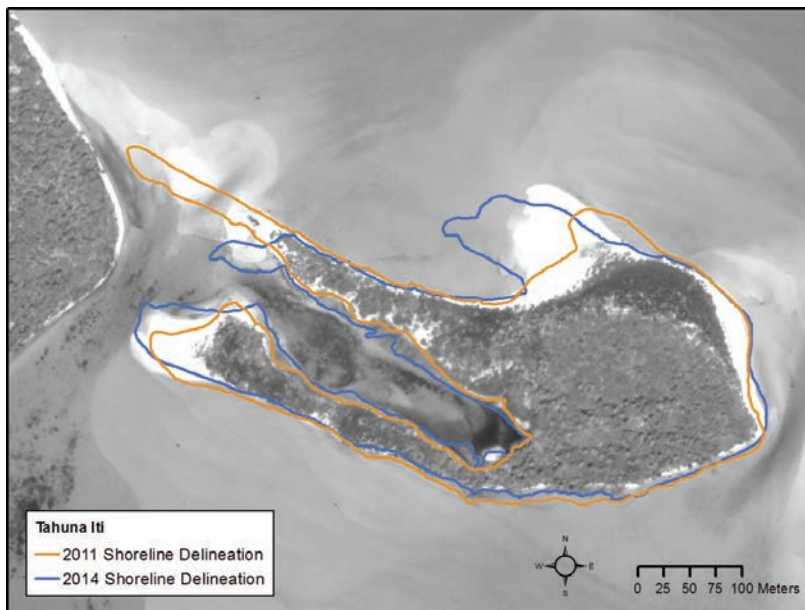


Figure 21.13. Aerial imagery from 2012, with 2011 and 2014 shoreline delineations. Image courtesy of Digital Globe. Data and cartography by University of Redlands, compiled by David Smith.

Fortunately for the ground-nesting birds, the sand spit that was growing toward rat-infested Rimatu'u was blown out between the 2011 delineation and the 2012 image. Erosion on the southeast side of Tahuna Iti was observed, with sand deposited on the north and northwest sand spits. The continual collapse and growth of the sand spits from south to north results in the motu shifting approximately 1 m/yr. A continual progression of sand spits growing toward the northwest is evident with an overlay of the team's delineation of the motu in May 2014. This imagery depicts the deeper water to the south of Tahuna Iti, the shallower water to the north where the sand erosion of the motu is being deposited, and the expanding sand spit at the westernmost point of the motu. The sand spit is growing closer to Rimatu'u and creates another potential bridge for the rats on the neighboring motu. The elongating sand spit will be something to watch during future research when the team returns to Tetiaroa.

Beach erosion, with vegetation falling into the lagoon along the windward shore, is noted on the shoreline delineation feature classes. From this data, the research team noted that the motu has moved approximately 3 to 4 m in just four years, which is consistent with the initial hypothesis that the motus are moving 1 m/yr. Tahuna Iti and the other southeast-facing islands of the atoll all exhibit windward beach erosion, with trees and shrubs exposed and falling into the ocean. Coconut palm root bases appear as dark spots just offshore of Tahuna Iti (figure 21.14). The eroded sediments then travel by longshore drift to the leeward (northwesterly) beaches, extending into long sand spits, as evidenced by Tahuna Iti, Rimatu'u, and Aie motus. When compared with a georeferenced 1955 aerial photograph of the atoll, the centroid for Tahuna Iti has moved by as much as 50 m in the 56-year reference period, with windward-to-leeward movement of 1 to 2 m just since 2010, as shown in figure 21.15.



Figure 21.14. A low-flight aerial photograph with a ground control point. Coconut palm root bases that appear offshore represent the pace at which the motus are shifting. Photo courtesy of David Smith.

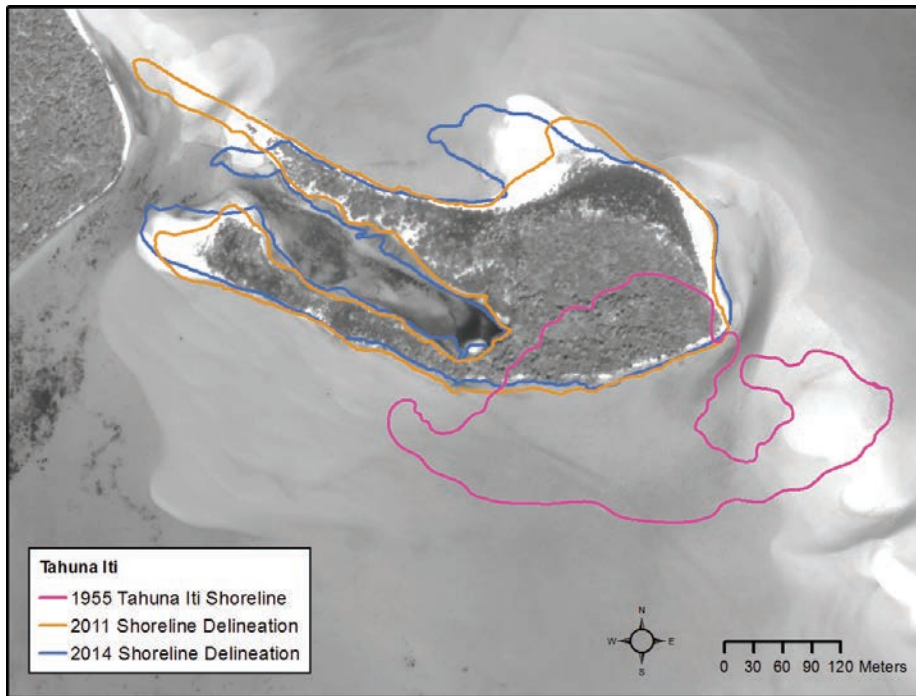


Figure 21.15. Aerial imagery from 2012, with 1955, 2011, and 2014 shoreline delineations. Image courtesy of Digital Globe. Data and cartography by University of Redlands, compiled by David Smith.

Conclusion

Exploratory work conducted by teams of University of Redlands students has demonstrated the potential for conducting high-quality research with relatively low-cost geospatial technologies. KAP conducted by students shows promise as a remote-sensing tool, and workflows have been established for producing georeferenced photomosaics of the atoll. Lessons learned include the overlap between images that KAP requires, the optimal altitude of the flights, establishment of sufficient ground control points to be seen in all images captured during KAP missions, and how frequently images should be captured during flight. Georeferenced egg counts of ground-nesting birds have been conducted, and limitations of GPS technologies under heavy canopies on the atoll have been noted. Plans for improving the spatial accuracy of data points gathered under heavy canopies have been developed.

The product of the Tetiaroa research effort has been the establishment of a thorough geographically referenced base datum for Tahuna Iti by which changes in the island geomorphology and biology can be monitored in coming years. Analysis of historical aerial photographs (the oldest available being 1955) and the fieldwork in the atoll over the last 60 years, including the most recent research in 2011 and 2014, indicates that the centroid of the islet has moved by as much as 50 m since that time. In fact, comparison of the shoreline delineations of Tahuna Iti in 2011 and 2014 shows a 1 to 2 m offset of the shoreline from southeast to northwest in just that three-year period. The KAP provides clear, geographically referenced evidence of the windward erosion of sediments, with wave-cut scarps and undermined vegetation, and coconut trees falling into water with remnants of old coconut root systems visible where trees grew just a few years earlier.

More recent aerial imagery from 2012 further indicates the windward erosion and leeward deposition of sediments, showing the movement of sand spits on the leeward shoreline of Tahuna

Iti toward its neighbor island, Rimatu'u. The 2011 shoreline delineation showed an extension and closure of the channel that separates Tahuna Iti from Rimatu'u to just 20 m wide and less than 1 m deep. Since then, the 2014 KAP imagery shows the channel blown out again, perhaps by an intervening storm or cyclone, with an entirely new sandy beach developing from the north shore of Tahuna Iti. If these processes of windward to leeward erosion and deposition continue, there is a very real risk that Tahuna Iti may be connected across the narrow channel, providing a land bridge for rats to cross from Rimatu'u and destroy the ground-nesting bird colonies on the island.

The georeferenced database for Tahuna Iti, and for Tetiaroa as a whole, provides a basis to monitor changes in shorelines over time. These spatial datasets can also be used to establish a program for monitoring the ground-nesting bird census plots, as well as for other biological research. With the Tetiaroa research program in place and high-resolution aerial imagery generated by ongoing KAP, future research teams will be able to watch the process over the coming years. To the extent that this knowledge can inform action, they can make recommendations with regard to channel stabilization and erosion control measures to ensure the survival of Tahuna Iti and its ground-nesting birds.

Acknowledgments

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Supplemental Resources

Dawn J. Wright, ed.; 2016; *Ocean Solutions, Earth Solutions*, second edition; http://dx.doi.org/10.17128/9781589484603_21d

For the digital content that goes with this chapter, explained as follows in this section, go to the following links or QR codes. Hyperlinks are also available in the book's online resources (esri.com/esripress-resources/ocean-solutions-2e).

Story Map App

- Tetiaroa Map Journal (Live), at <http://arcg.is/1F4T1Za>



This Story Map app chronicles the adventures of a group of students and faculty from the University of Redlands (including several of the authors) while participating in a travel course to French Polynesia to study various applications of environmental science on the atoll named Tetiaroa. The team's objectives were to study one of the last ground-nesting bird populations on Earth, as well as to gain an understanding of island geomorphology by evaluating the ongoing changes in shoreline position using kite aerial photography. This Story Map app was also presented as a full-length oral presentation at the 2014 Esri Ocean GIS Forum.

Online video

- *Tetiaroa KAP (Kite Aerial Photography) High Flight*, at <http://bit.ly/TetiaroaHighFlight>



A realistic interactive virtual flyover that allows the user to stop the motion at any point, and zoom and pan. The video was created with Microsoft Photosynth, a cloud-based platform for producing “immersive 3D experiences.”

CHAPTER 22^{New}

Sediment Drainage Streams Important in Benthic Seafloor Classification

Chris Jenkins

Abstract

Analysis of bathymetry datasets identifies seafloor stream features that appear to be the conduits for downslope transport of sediments across continental margins. The stream networks occur in addition to other features caused by current/wave transport processes. Taking the northern Gulf of Mexico as an example, the conduits (hollows, channels, and canyons) join into an extensive sediment drainage network. The pattern reflects the importance of bottom-concentrated sediment flows across all benthic environments, essentially attributable to particle-settling physics, and turbulence in benthic boundary layers. The sediment drainage network is a source of patchiness in sedimentary facies and biological communities, so it is a suitable classifier of the seabed. Furthermore, the sediment drainage network provides a framework for source-to-sink modeling of sediment and trophic supply to the deep sea.

Introduction

Environmental classification of seafloor areas is performed today to better understand the distribution of biological resources and, in policy, achieve a balance between exploitation and conservation. In many cases, the classification is done using geomorphic provinces (e.g., Heap et al. 2005), but it is not clear that organisms are significantly aware of (experience) factors on that scale. Statistical examinations cast doubt on that approach (Przeslawski et al. 2011). More likely, the biological populations respond to processes on smaller scales corresponding to positioning and mobility (if any), relationships to food and competitors, reproduction modes, and the extent of water/sediment motions during their life-spans. A process-based approach at maximum practical resolution is more defensible logically using factors such as benthic irradiance, sediment geotechnics, bottom shear

stress, organic carbon fluxes, and oxygen content. This type of process-oriented approach was used in the UKSeaMap classifications (Connor et al. 2006) and is since being more widely adopted.

Following the focus on processes, this chapter explores the possibility of using bathymetric features, which are the probable modern-day paths for sediment drainage, for seafloor classification. In this case, drainage refers to downslope sediment gravity movement, assisted by other transport mechanisms such as wave/current traction and saltation, and liquefaction. The pathways are variously canyons, valleys, channels, funnels, chutes, and hollows. They occur in addition to features from other processes of transport and buildup at the seafloor. They can be identified in bathymetry using software co-opted from on-land river studies. Many pathways are continuous over long distances, and they are interconnected and form a network.

Extracting Sediment Drainage Networks

The current global bathymetry Shuttle Radar Topography Mission 30 Plus (SRTM30_PLUS) dataset (Sandwell et al. 2014) is, in many areas, sufficient for preliminary analysis and assessment of valley structure. The techniques described here may also be applied to the small amount of the ocean that has been mapped to higher resolution—for instance, using multibeam sonars. By using the global bathymetry to start, the possibility of applying the technique anywhere in the world is left open.

The software TauDEM (Tarboton 2003) is applied to the global bathymetry, at 1/120 degree (~0.8 km) grid resolution. This software was developed to delineate river networks in terrestrial settings, but it is essentially geometric in operation and, perhaps with minor adjustments of settings, is applicable to underwater sediment flows. In any case, it is a suitable demonstration of ideas. TauDEM analyzes the slope magnitudes, curvature, and directions in an elevation grid and connects the cells by computing the likely downward paths. Two methods are used: single path (D8) and multipath (Dinf). Once the flow paths are identified, various statistics are generated, including total river-channel length, channel catchment area, and length of steep slope along channel. Furthermore, with a channel network defined, many other forms of analysis are valid (Tarboton and Baker 2008).

Figures in this chapter illustrate the application of TauDEM to a relatively well-understood part of the seafloor, the northern Gulf of Mexico (NGoM). The bathymetry (figure 22.1) and TauDEM analysis results are presented on a geographic grid (WGS84 spheroid and datum). Figure 22.2 shows the drainage network computed using the Dinf process, proportional flow directing. Several features are worth pointing out. First, the method correctly picks the submarine canyons and valleys that are obviously conduits for sediment transport. Regions with different patterns of drainage are clearly distinguishable.

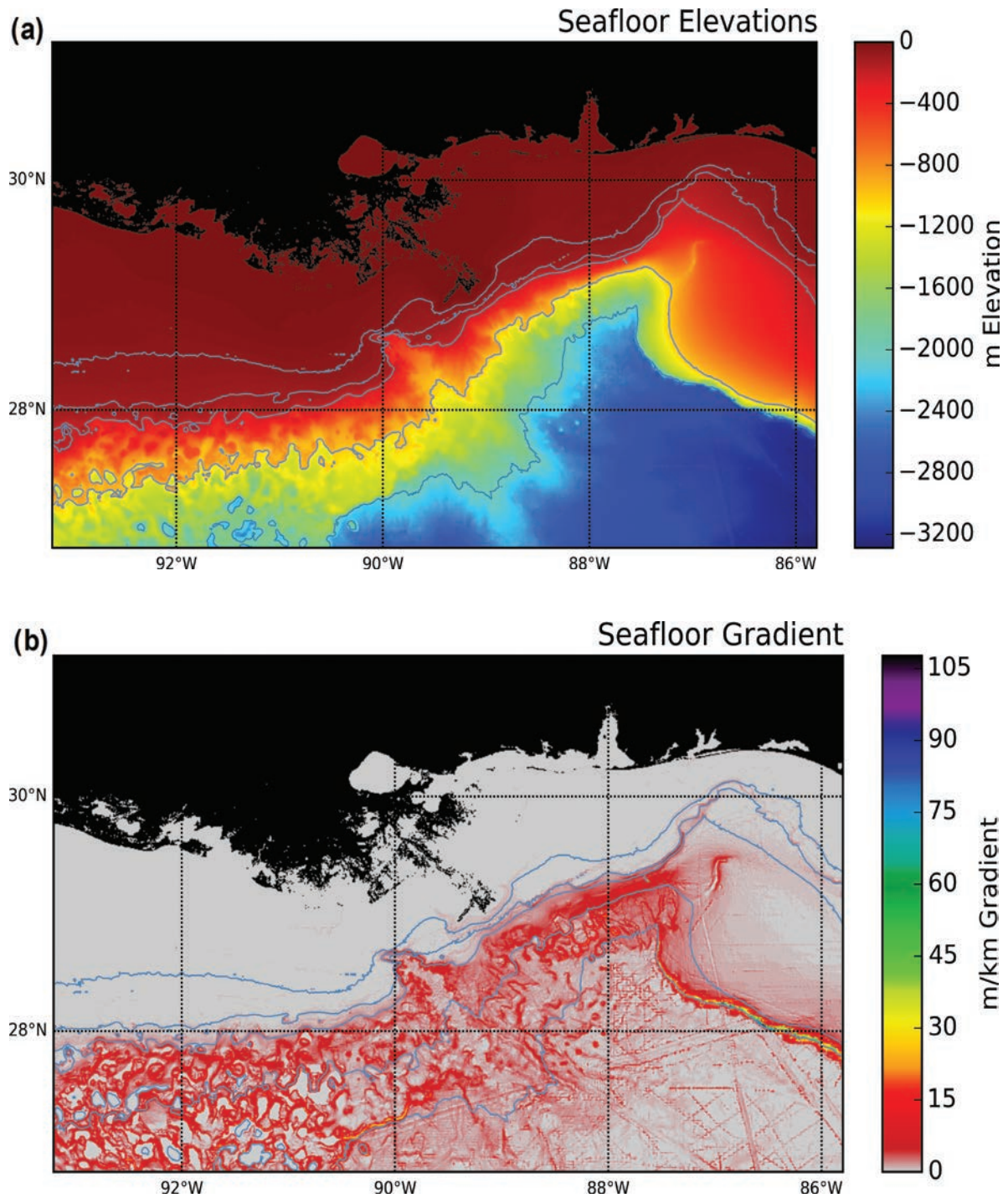


Figure 22.1. Bathymetric basis for the analysis: (a) colored and contoured mapping of the seafloor bathymetry, northern Gulf of Mexico, based on the SRTM30_PLUS dataset. The 50, 100, 200, 1,000, and 2,000 m water-depth contours are drawn (*teal color*) in this and other figures. (b) Seafloor slopes at 1 km cell resolution, northern Gulf of Mexico based on the same dataset, highlighting the complex morphology of some areas. *Middle:* Mississippi Canyon. *Right:* Florida escarpment. *Bottom left:* Sigsbee escarpment.

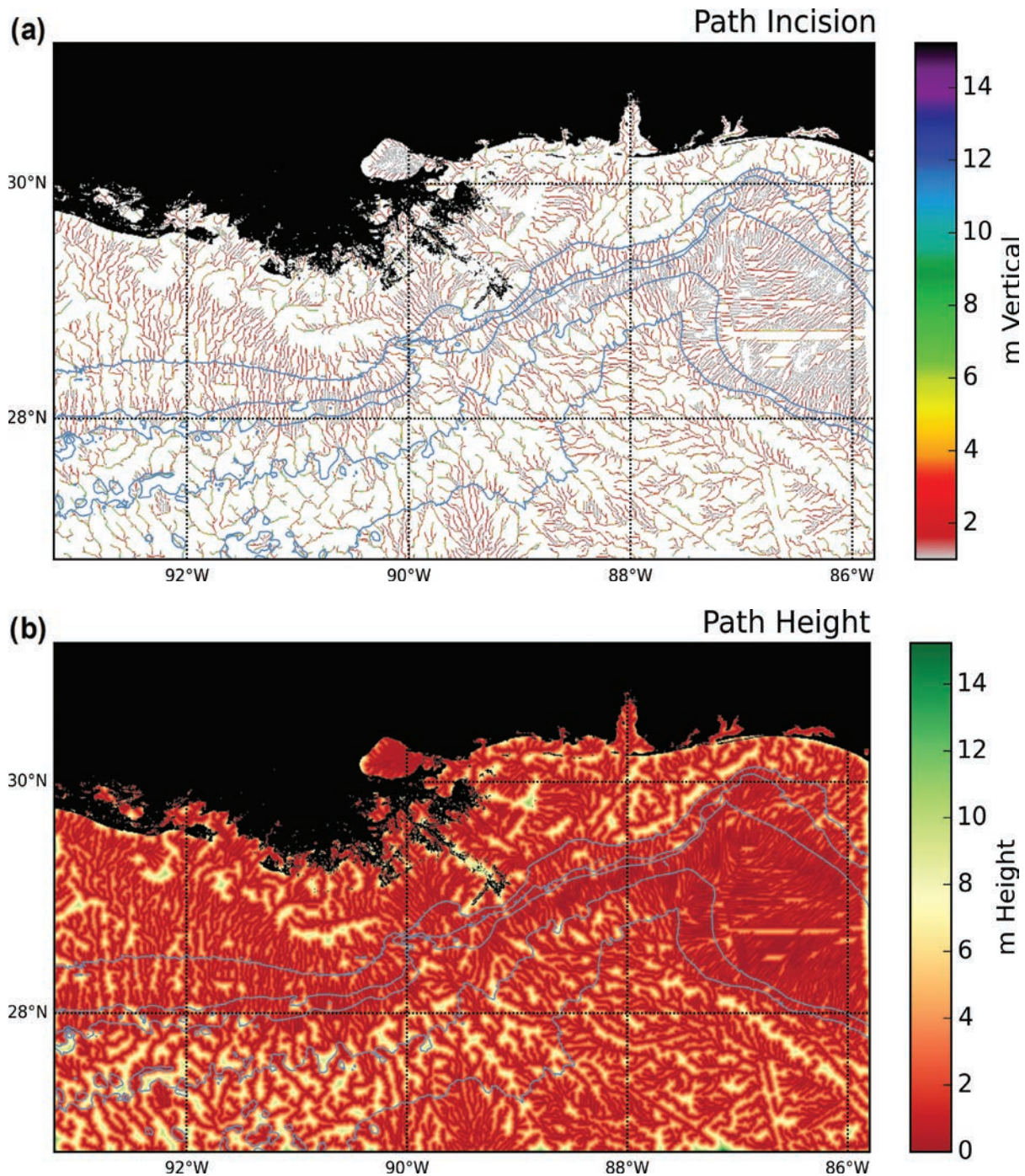


Figure 22.2. The identified drainage streams pattern, northern Gulf of Mexico: (a) topographically defined sediment drainage pattern for the same area, computed using TauDEM. *Gray/red* streams have least incised relief and are the most common, *green/blue* streams have incision up to 15 m on kilometer scales of gridding. And (b) delineation of drainage (*red*) and interfluve (*yellow-green*) areas in terms of distance to streams.

At finer levels of detail, cross-shelf channels are identified, mostly originating from estuaries. They appear to mark locations of cross-shelf sediment flows especially for extreme events. They are deflected by submerged ridges on the shelf, notably Ship Shoal 40 km seaward of Terrebonne Parish (Louisiana) and the Chandeleur barrier islands east of New Orleans. West of the Mississippi River

Delta, the paths gather from shelf areas to the northwest and from the delta and focus into the head of the Mississippi Canyon as expected. The network patterns down the main continental slope are reasonable, especially in the area of the Mississippi Canyon down to depths of 2,000 m. In the area of the outer shelf near De Soto Canyon, seaward of the Alabama coast, the paths navigate through gaps in the outer-shelf rock ridges such as the Alabama Alps offshore of Mobile, Alabama (Weaver et al. 2001).

Long and short paths are identified on the abyssal areas. Twichell et al. (1991) employed the midfrequency side-scan sonar Geological Long Range Inclined Asdic (GLORIA) to delineate a form of main channel for the Mississippi fan, which meanders and passes generally southeast of the mouth of the Mississippi Canyon to 3,000 m water depth. This course is considerably south of the main computed drainage path that exits the canyon mouth, and it follows a topographic hollow trending east-southeast on the eastern flank of the Mississippi fan sediment buildup. Although this seems an error at first sight, the GLORIA-defined channel is a Pleistocene feature (Pickering et al. 1986), mantled where cored by 20 cm of Holocene calcareous ooze, indicating that it is probably inactive in the present day. The channel computed in TauDEM therefore remains quite a feasible path for present-day bottom flows in the region. Present-day bottom-following flows will deviate around areas of sediment buildup just as with any other topography.

Remaining Issues

The global bathymetry, in common with others such as the National Oceanic and Atmospheric Administration (NOAA) coastal relief model (Eakins and Grothe 2014), contains noisy data. Trackline effects are sometimes obvious and can potentially affect the TauDEM results. However, in the results they have minor effects. In any case, the problem will diminish as bathymetric datasets improve in quality and resolution. Using TauDEM out of the box may not always suit submarine situations. The “pit removal routine” may be unnecessary for sediment-laden flows. TauDEM does not identify dividing channels such as those that occur in delta and submarine fan distributary networks. Valley structures at the seafloor are subtler than on land. Note that in common with all digital elevation models, stream delineation is sensitive to grid resolution and insensitive to subgrid topography that may be revealed in future higher resolution mappings. For uncertainty in calculations, the paths can be rated and perhaps filtered out by their incision (see later) compared with the stated accuracy of the input SRTM30_PLUS data, which is estimated at better than 10 m in most parts of the NGoM. Obviously, the smaller the incision of a channel, the greater the uncertainty in the associated calculations.

Further Analysis of Paths

More advanced analysis of the channel pattern focuses on two aspects: the drainage paths themselves and the interfluvies between them. Looking at the paths, two metrics of interest are (1) the down-channel bed-slope, obtained by querying the regional slope at each channel pixel, and (2) the incision of channel, obtained by querying a 3×3 or larger domain of grid cells around the channel trace. Both metrics have found a practical application recently in numerical modeling of upper-slope turbidity flows induced by sediments that are resuspended during extreme events such as hurricanes (Birchler et al. 2014).

The spatial pattern of interfluvial areas was computed by distance buffering and also by nearest neighbor operations relative to the drainage path data. The results are similar. An additional mapping of the interfluvial cell height above the nearest channel cell (figure 22.2b) suggests the incision or relief associated with the drainage channels on horizontal scales of several kilometers.

Gravity Processes

The significance of the mapped drainage paths to sedimentary and benthic community patterns stems from the fact that most marine sediment transport is bottom concentrated and therefore steered to a significant degree by bottom gradients and features. The paths suggest a set of locations for unstable benthic sediment movement and changing bed levels, separating areas of stability and steady deposition. Gravity-driven flows on continental slopes and abyssal plains are well documented. Submarine canyons and turbidite channels (Harris et al. 2014) are prime examples. But abundant evidence also has been found for gravity-driven sediment flows on continental shelves (Wright and Friedrichs 2006). Frequently, a receiving submarine canyon is identified nearby. The cross-shelf flows may originate in different ways: strong near-bottom wave-supported sediment resuspension (Traykovski et al. 2000), downwelling of coastal flows, and liquefaction of the topmost sediment bed (Puig et al. 2004). Amos and colleagues (2003) observed perennial, shore-normal furrows passing from the shoreface of Sable Island (eastern Canada) down to 40 m water depth. The formation mechanism is thought to be erosion by seaward-directed inner-shelf turbidity currents that transport sediment and detritus. In another setting, sediment-laden meltwater gullies traverse Antarctic shelf areas (Noormets et al. 2009). In normal shelf settings, cross-shelf (“diabathic”) transport can be important for littoral sediment budgets (Finkl 2004). To summarize, sediment transport by gravity processes is often localized to streams and is widespread and diverse. The present mapping based on bathymetry data creates a framework for understanding and modeling the flows.

Of course, gravity-driven sediment transport is not always dominant, notably in shallow-water settings in which wave and current transport dominates and may create special bottom topography. But even in these settings, most sediment flows are bottom concentrated because of two factors: grain settling and the focus of energetic turbulence in the benthic boundary layer (BBL). In the sandy environments of the continental shelves, near-bed rolling and saltation dominate transport modes. Over 0.9 to 0.99 of saltation grain concentration occurs in the bottom 20% of flow depth (e.g., data in Van Rijn 1984), corresponding to the exponential theoretical Rousian concentration profile (Dyer 1986). Even fine particles freshly discharged from rivers settle quickly toward bottom, dominantly at rates of 10 to 100 m/day (e.g., Syvitski et al. 1995). In muddy areas, an extremely concentrated fluid mud often settles on the seafloor even shortly after storms, as in the inner-shelf region of the Mississippi delta (Jaramillo et al. 2009). These fluid muds, typically less than ~0.2m height above the stable seafloor, are observed to be slightly in motion, responding to overhead wave forcings.

The energy for sediment resuspension under waves and currents is concentrated in a turbulent benthic boundary layer. Depending on forcing scales and bed roughness, BBL heights vary from centimeters, for waves (Warner et al. 2008), to on the order of 10 m, for currents (Weatherly and Martin 1978). Based on many sets of monitoring data, the observed vertical scale of sediment-laden BBL flows is less than several meters (usually <1 m). These thin vertical scalings imply that even meter-scale changes of seafloor elevation may work to significantly guide and localize the wave- and current-driven sediment transport and deposition.

Conclusion: Source to Sink Considerations

Identifying the network of sediment drainage paths for a region opens the way to a better, spatially explicit understanding of sedimentation patterns and trophic supply to benthos. Sediment and trophic particle fluxes and erosional–depositional stability of the bottom are understood to be important controls on benthic community structure and biomass (Rowe and Kennicutt 2009). Especially when the draining sediment is sourced at vegetated coastlines, the entrained organic materials including wood provide “new carbon” to deep-sea communities. Conversely, bed-level instabilities will disrupt positioning, feeding, and reproductive strategies. Without being more specific, it is clear that an active sediment-draining network in a region allows for community patchiness and diversity.

The importance of the stream network in marine areas is that it provides a framework for further analysis and modeling. Using the network to spatially query other datasets, information about sediment types and trophic factors can be propagated through the network from source to sink. For example, sediment compositions in the source areas are documented in the US Geological Survey’s usSEABED database (Arsenault et al. 2010; Williams et al. 2012). Source-area coastal vegetation is documented in Spalding et al. (2010). Data on the fine-sediment discharge from the world’s large rivers is available from HydroTrend calculations by Syvitski and Kettner (2011).

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CHAPTER 23^{New}

The Navy Shore Geospatial Energy Module

Amanda Williams, Sandrine Schultz, and Greg Turner

Abstract

The US Department of the Navy values energy as a critical resource that enhances operation reach, energy security, and energy independence. It is also leading the charge in leveraging geospatial technologies to reinforce and sustain a navy culture that recognizes energy as a key combat enabler. Although much of the navy's operations occur at sea, the navy has embarked on several aggressive strategies to reduce consumption and increase energy intensity; and it has provided 1 gigawatt of renewable energy on or near shore installations. To achieve navy shore energy goals and provide users with actionable information, the Commander, Navy Installations Command has developed the Navy Shore Geospatial Energy Module, which is a central platform that connects relevant facility and utility data systems to synthesize energy-related knowledge and measure performance. In 2014, the Commander, Navy Installations Command was awarded the Esri Special Achievement in GIS Award for innovation and intelligence with this project. This Esri award honors outstanding applications of geospatial technology. The Navy Shore Geospatial Energy Module technology provides a common source of information and capability that engages all stakeholders and helps them decide where the best return on investments can be implemented. It also provides the ability to monitor goal achievements, perform facility-level measurement and verification, and generate required reports. The system provides transparency to increase awareness, educate and train personnel to value energy as a mission-essential resource, develop the workforce with skills to manage energy and reduce energy-related risks, and promote solutions to energy management challenges. The Navy Shore Geospatial Energy Module's components are aggregated to present a holistic picture for energy plan development.

Introduction

Commander, Navy Installations Command Program Overview

The Navy Shore Geospatial Energy Module (NSGEM) provides a geospatial toolset to meet the requirements of Executive Order 13963 (replacing EO13423 and EO13514). It is the first service-based response to climate change that recognizes climate change as a geographically organized problem. This effort recognizes that energy requirements are geographically driven, energy alternatives are geographically driven, and these requirements are fundamental to resilient planning for sustainable naval operations.

The Commander, Navy Installations Command (CNIC) Energy Program was instituted to provide guidance, policy, and tools for implementing mandated energy reduction and sustainability practices. To achieve energy independence from a finite petroleum supply and lead the nation toward a clean energy supply, the US Department of the Navy (2015) has been developing a strategic plan to reduce energy consumption, as well as integrate alternative energy sources. The main goals of the program, as outlined in the Chief of Naval Operations (OPNAV) Policy OPNAVINST 4100.5E (Chief of Naval Operations Shore Readiness Division 2012), are to achieve

- 50% ashore consumption reduction from 2003 baseline by 2020,
- 50% total ashore energy from alternative sources by 2020,
- 50% installations net-zero consumers by 2020, and
- 50% petroleum reduction used in the commercial vehicle fleet by 2015.

To meet these goals, CNIC adopted a facility energy strategy that includes reducing energy demands (facilities and building practices using less energy consumption), expanding energy supplies (adopting alternative/renewable sources), enhancing energy security (sustainable energy usage), and advancing new technologies (such as installing smart meters on each building and using GIS to leverage and provide metrics from available consumption information).

CNIC recognizes that the navy's shore energy strategy is to achieve legal compliance and greater energy security through increased efficiency, transform the navy's energy culture, and integrate viable renewable energy sources and sustainable construction practices. Specifically, the navy's PB-12 Shore Energy goals are to reduce consumption by 50% by 2020 and provide reliable, redundant, and resilient energy to Navy Tier I/II Critical Assets by 2020. Additionally, CNIC Navy is aware of the significant monetary implications of energy consumption and the demand it places on annual budgets. Through improved financial execution and planning of energy projects, the navy will receive significant fiscal and strategic benefits. Part of the Department of the Navy (DON) effort is to effectively manage energy consumption and lead in energy innovation to assure superiority in the execution of its national defense mission. There are three key components to the program: energy efficiency, renewable energy and sustainability, and culture and behavior (US Navy Energy, Environment, and Climate Change 2015). The DON seeks all measures to minimize energy consumption; reduce energy expenditures; and use alternative energy resources and environmentally sustainable technologies where it is reasonable, affordable, and practical to do so (figure 23.1). Energy projects are monitored to ensure that costs and savings are verifiable and that energy-efficient shore facilities contribute to operational effectiveness. Stakeholders include the office of Secretary of the Navy (SECNAV), office of the Chief of Naval Operations, CNIC, Naval Facilities Engineering Command (NAVFAC), the Renewable Energy Program Office (REPO), Public Works Business Lines, Regional and Installation Energy Managers, and Tenants and Bill-Payers (figure 23.2).

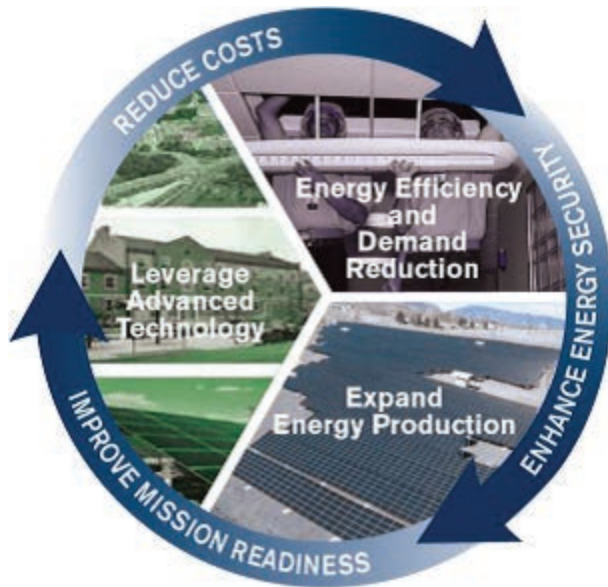


Figure 23.1. Commander, Navy Installations Command's shore energy strategy. Courtesy of CNIC Energy Program.

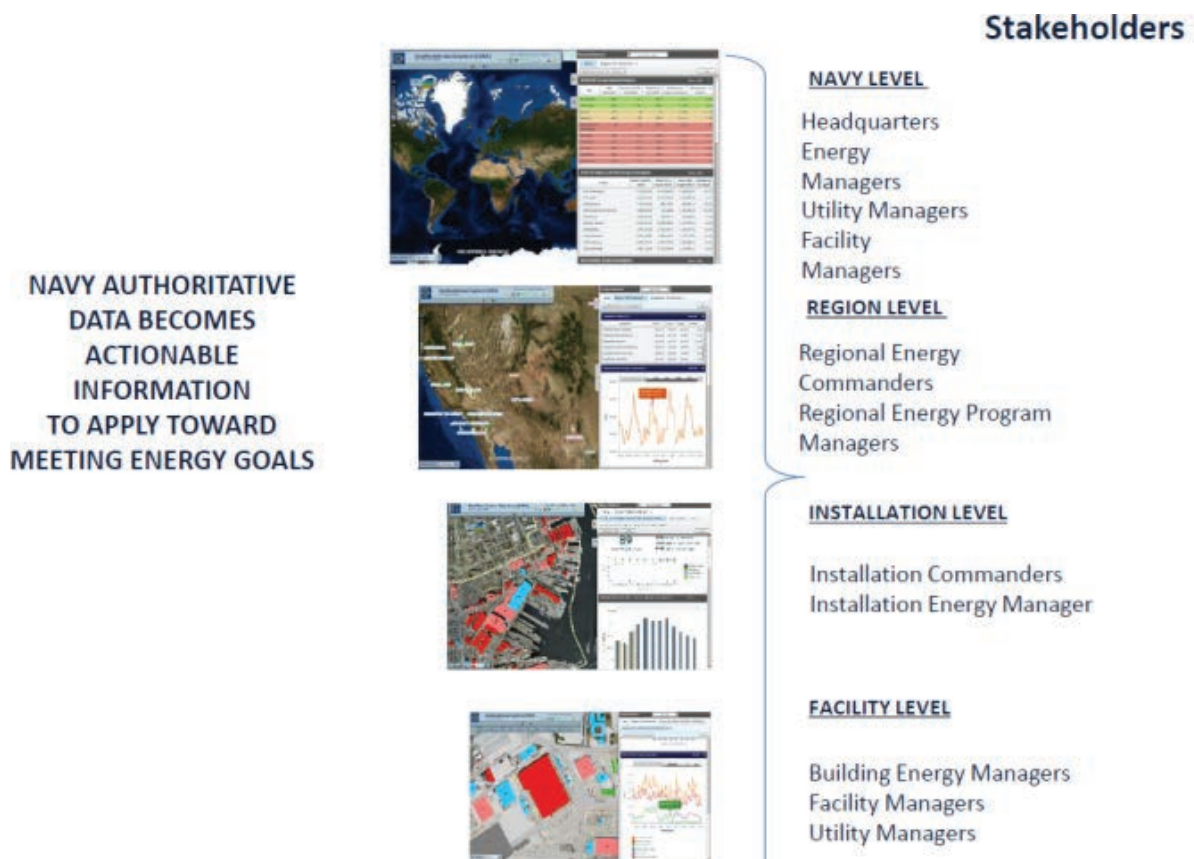


Figure 23.2. Breakdown of the Commander, Navy Installations Command energy stakeholders at each operational level. Courtesy of CNIC Energy Program.

CNIC Energy Tool Suite

NSGEM is built on the Navy Common Installation Picture (CIP) geospatial facilities dataset and the GeoReadiness Explorer (GRX), which allows for geospatial visualization and analysis of the CIP data. NSGEM adds navy energy consumption visualization and analysis, as well as standardized reporting capabilities, to the GRX Viewer. In order for the navy to achieve its energy goals, a suite of tools was developed specifically for the CNIC Energy Program. These tools work together to aid navy installations in learning what their goal consumption should be on the basis of modeled and actual data from energy consumption and to enable installation energy managers to design energy projects at the facility level. The main tools used in this process include the geospatial component (NSGEM), goal and benchmark component (Goals Package), project development component (Energy Return on Investment), and the investment portfolio to review performance against the navywide energy mandates (Shore Energy Implementation Portfolio).

NSGEM is an interactive web map that uses information from authoritative data systems to visualize monthly energy use navywide. More specifically, NSGEM color-codes all facilities according to their energy use benchmarks; assesses data completeness within authoritative sources and encourages users to update missing or incorrect information; and produces energy consumption reports for various levels: navy, installation, region, facility, and tenant. NSGEM also works to improve energy-related situational awareness and decision-making, providing a unified system for access and analysis of information. NSGEM adds value to existing energy business systems and data by geospatially enabling the data for understanding and display and increasing the user base and use of GRX through the energy program.

The Goals Package is a dynamic analysis tool for benchmarking energy consumption and identifying efficiency opportunities for achieving the navywide 50% energy reduction requirement. This tool has the most direct tie to NSGEM in the entire CNIC Energy Tool Suite, as the majority of the data reported in NSGEM is based on the Goals Package. The Goals Package models missing utility data to provide complete information for all facilities, calculates benchmarks by climate and building type, tailors energy reduction goals by installation and region, suggests potential project concepts (modeled energy conservation measures) to reduce energy and costs, and combines all applicable facility energy management data into one centralized report and list of Energy Conservation Measures reports. The Goals Package integrates authoritative utility and facility data systems and fills in gaps to develop the facility energy use dataset. Data from the Internet Naval Facilities Assets Data Store (iNFADS) real property management system and Centralized and Integrated Reporting for the Comprehensive Utilities Information Tracking System (CIRCUITS) Utilities Allocated (UA) (utility consumption) is used to calculate energy use intensity (EUI) and determine appropriate benchmarks. The Goals Key Statistics report the resulting facility energy use dataset and data quality of authoritative systems, producing three reports on data quality for each echelon:

- Data Quality Scores: scores the data consistency between iNFADS, CIRCUITS, and Defense Utility Energy Reporting System (DUERS) data;
- Exceptions Report: reports on mismatched and missing data in iNFADS and CIRCUITS (sent to NSGEM); and
- Facility Data Report: captures facility energy use versus benchmarks and identifies outlier facilities (sent to NSGEM).

The Goals Package models and prioritizes the most cost-effective energy efficiency opportunities to allocate installation reduction targets. The Goals Package models energy efficiency opportunities using two inputs: facility reduction potential (facility energy use above the benchmark) and potential

facility projects (sample projects by facility type). Facility reduction potential is the difference between actual consumption and the benchmark for a facility's performance. Benchmarks for each building type and climate zone are based on American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 90.1-2010. Common building types use these benchmarks directly, while navy-specific building types use customized benchmarks based on statistical analysis. Potential facility energy conservation measures (ECMs) are developed by mapping ECM templates to facilities by building type. The Goals Package allocates energy reduction targets by selecting modeled energy ECMs across the navy, prioritized by simple payback, and fairly allocates energy reduction goals across Installations, as well as setting optimized reduction targets to achieve the greatest financial benefit to the navy.

The Energy Return on Investment (eROI) is a user-friendly, web-enabled tool that facilitates project development and ensures financial viability. More specifically, eROI ensures that project investments are comparable and yield favorable returns, develops a weighted score using energy and nonenergy benefits (i.e., energy reliability, regulatory compliance, infrastructure improvements, operations, and maintenance avoidance), informs installation energy managers of funding likelihood via weighted scoring, and centralizes energy project data circa fiscal year 2012.

Finally, the Shore Energy Implementation Portfolio (SEIP) is an energy investment portfolio that reviews and forecasts navy, region, and installation performance toward achieving navywide energy mandates. More specifically, SEIP captures all navy energy projects (past, present, and future); summarizes energy management trends, projects, and compliance progress; analyzes the effectiveness of all navy energy investments; and establishes future funding requirements to meet navy objectives.

Together, the CNIC Energy Tool Suite enables navywide standardized project planning, reporting, and tracking across all installations. For example, an installation energy manager who wants to figure out the best facilities to focus energy projects on would start by looking at their energy use intensity and benchmark scores in NSGEM. By starting with NSGEM, they can quickly and easily determine data gaps, as well as generate standardized reports on their facilities and overall consumption picture. The user would then begin project planning and moving through the rest of the CNIC Energy Tool Suite products to design, forecast, and track energy projects (figure 23.3).

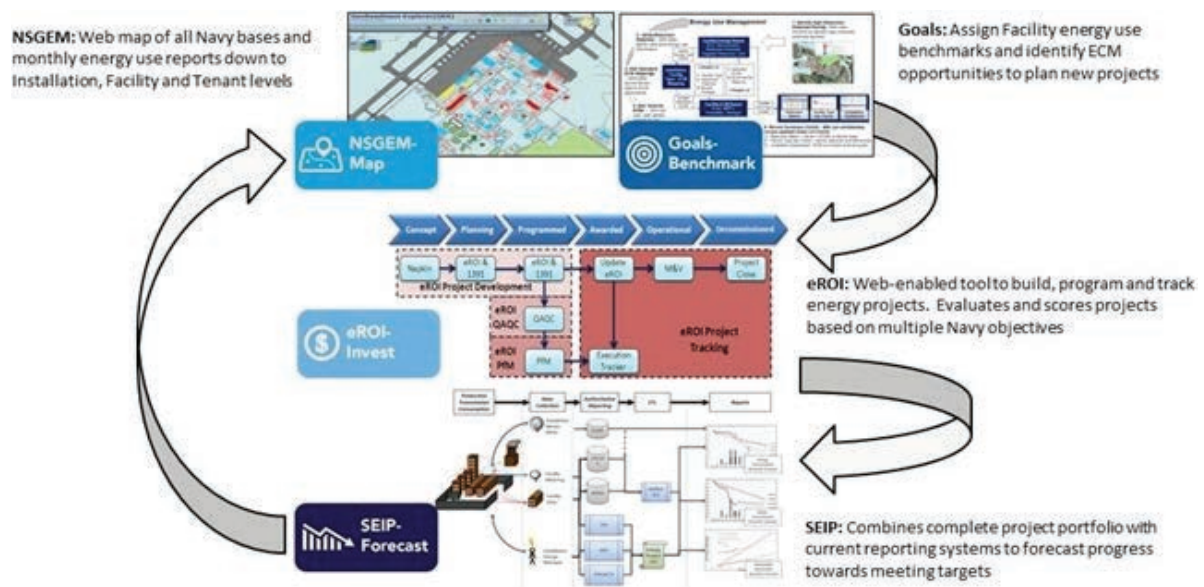


Figure 23.3. Example life cycle of a navy shore energy project. Courtesy of CNIC Energy Program.

Focus on Geospatial Technology

The NSGEM geospatially enables the CNIC Energy Program with standardized tools and reports to track and measure progress toward reduction goals, pinpoint specific areas for improvements or restorations, view new and alternative energy sources geospatially, create sustainable practice methods, and increase overall energy usage awareness. NSGEM provides the CNIC Energy Program with a “one-stop shop” for viewing and using energy consumption data from different perspectives. Additionally, NSGEM provides a snapshot of data discrepancies that may prevent an installation from reaching its energy consumption reduction goals. CNIC and NAVFAC now have the ability to reveal the story of data that has been isolated to an individual business system (e.g., NSGEM) and to smoothly and dynamically transition across all necessary temporal (many months and years), spatial (integrated web map view), and organizational (world, region, installation, and facility) scales.

NSGEM enables the navy to implement Installation Geospatial Information and Services (IGI&S) data and capabilities by directly supporting the mandated energy program. This structure allows for increased knowledge and access of energy-related data, as well as synthesizing new energy-related knowledge. NSGEM also aggregates key authoritative data from systems and programs of record, such as CIRCUITS, iNFADS, and Worldwide Common Installation Picture (WW_CIP) data. Energy projects may also be linked at the facility level, especially with the addition of microrenewable energy projects planned and implemented at this scale. NSGEM is tailored to IGI&S-related GIS capabilities to meet energy decision-maker needs and also develops analytical GIS-enabled energy tools. NSGEM creates a common source of information and capability that engages all stakeholders, provides tools that enhance interaction between energy stakeholders, improves and enhances energy stakeholder decision-making, and assists with reporting requirements.

Using the GeoReadiness Interface

The US DON is in the forefront of measuring and efficiently managing facility energy consumption. CNIC’s dedication to facility infrastructure management in execution of the navy shore energy program has generated the need for geospatial technology specifically designed for program measurement and verification. Through current methodologies in the navy’s IGI&S program, these spatial capabilities make it possible for the navy to leverage existing business line applications and to have developed NSGEM.

At the inception of the CNIC Energy Program, one of the first intentions was to develop a geospatially enabled solution to meet the navy shore energy mission, which included assisting with reducing consumption and increasing efficiency, as well as tracking energy progress via measurement and verification processes. After the development of this solution, the next phase was to include additional field user testing in the production environment, training, feedback from subject matter experts, and an emphasis on outputs that meet the needs of end users. To ensure that NSGEM meets the needs of end users, the intent was to open the application for end-user testing and provide comprehensive training resources, while also obtaining key input from the potential user community. Questionnaires, solicitations for information during testing, and an ongoing monitoring or feedback loop facilitated this process.

NSGEM Functions and Capabilities

The NSGEM application provides a multitude of capabilities. NSGEM is both flexible and scalable to enable future version enhancements. The basic graphical user interface (GUI) features an interactive web map, legend, links to external authoritative data systems, and basic interactive web map querying and navigation tools, as well as the specially customized Energy Dashboard. The Energy Dashboard (figure 23.4) is a unique data navigation tool that allows the user to explore energy consumption data at various stakeholder levels. These views are called “lenses,” which the user can specify in the dashboard and choose from the entire navy enterprise, region, and installation. At each lens, the map zooms to the full extent. Once zoomed into an installation, the user can select a facility from a drop-down list or click on the map. The user may also sort the facilities according to Tenant (party responsible for the facility) or Preponderant User (party who occupies the majority of space within a given facility). Additional dashboard functionality includes a chart picker, which allows the user to select from various charts to visualize energy data and to select predefined and customizable print-ready PDF reports (figure 23.5). The reports may include geospatial data displayed as a map (such as in the Regional Energy Map Books), as well as consumption and facility asset data, providing a total picture of what is being reported by the various authoritative data systems. There are also predefined Goals Package reports for each region and links to interactive external workbooks, such as the Facility Energy Workbooks housed on the navy’s intranet.



Figure 23.4. Navy Shore Geospatial Energy Module Energy Dashboard. Courtesy of CNIC Energy Program.

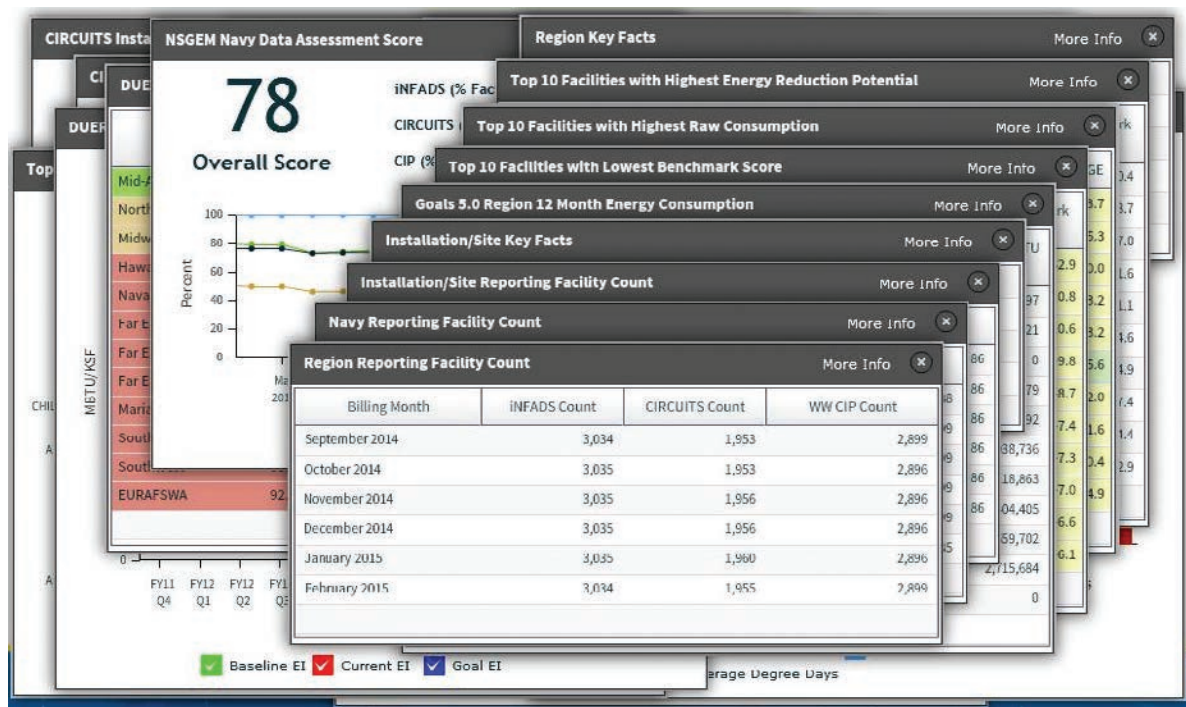


Figure 23.5. Example of various Energy Dashboard charts available at a selected installation. Courtesy of CNIC Energy Program.

Because its purpose not only is to display present-day energy consumption but also to compare trends and possible improvement since the inception of the project, NSGEM includes a temporal aspect. The dashboard includes a date picker, which allows the user to “step” through data on a monthly and annual basis. As data reporting has improved during gap analysis, data completeness, or Data Assessment Scores (DAS), can change over time. NSGEM is useful in highlighting data discrepancies, which allows an installation energy manager to review source data to ensure that the highest quality data available is reported.

Other NSGEM highlights include tenant energy consumption reports that increase accountability and influence behavior change, as well as use of energy benchmarking (the process of accounting for and comparing buildings’ current energy performance with their energy baseline); DAS, which indicate the completeness of data within authoritative sources and encourages user updates; and Regional Energy Map Books (REMBs), which provide a report on energy consumption for the region and installation accompanied by a map view of the installations within the selected region.

Incorporating Authoritative Big Data Systems

During the extract, transform, and load (ETL) process within NSGEM, a number of big data external authoritative business systems are incorporated, aligned, and filtered to produce the necessary information to meet the consumption reduction standards (figure 23.6). NSGEM consumes big data, in excess of two million records over the course of a year.

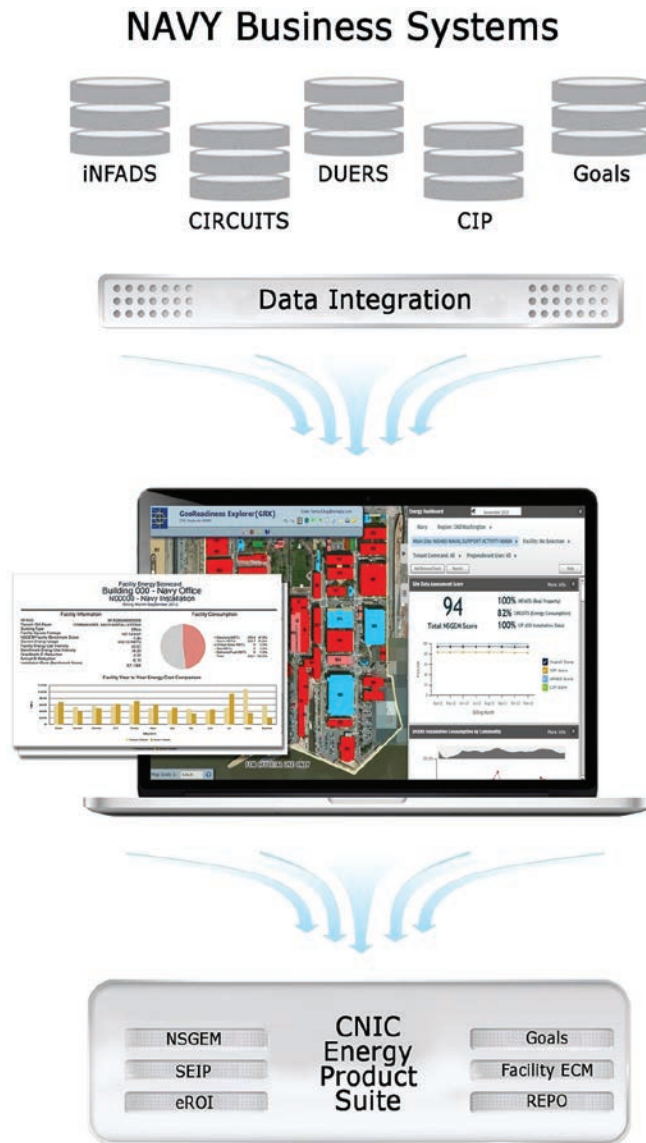


Figure 23.6. Overview of authoritative business system data incorporation into the Navy Shore Geospatial Energy Module and the other Commander, Navy Installations Command Energy Tool Suite products.

Courtesy of CNIC Energy Program.

Centralized and Integrated Reporting for the Comprehensive Utilities Information Tracking System

CIRCUIITS provides the utility allocation energy consumption numbers that the navy uses in the shore energy program. CIRCUIITS UA is the only utility allocation system that the navy uses. Although some facilities receive actual meter reads, a large number of facilities use allocated or estimated values based on consumption from a meter that may feed multiple facilities. Meters are the basis for the allocation, taking into account the values assigned to the end users within the facilities. CIRCUIITS UA is divided into two modules: (1) Client Modules, used by NAVFAC customers to review and generate reports about their utility usage; and (2) Administration Modules, used by UA staff to review monthly meter readings, assess end-use entities/facilities, process monthly allocations,

and create utility management reports. CIRCUITS feeds approximately 186,000 unique records into NSGEM each month, and these records are added to the totality of CIRCUITS data in NSGEM.

Business rules are applied to filter CIRCUITS data to account for the appropriate facility type, as well as commodity type. The same business rules are also applied to the Goals Package and other CNIC Energy Product Tool Suite projects to maintain consistency. Business rules that are applied include

- rounding up monthly data to annual values;
- removing all demand-based electricity use;
- converting thermal (THRM) (from KCF Technologies) and megawatt-hours (MWH) to 1,000 British thermal units (MBTU);
- converting Propane to Delivered Fuel;
- consolidating SteamProd, Stm/Htw, CogenSteam, and PBSteam under Steam;
- consolidating Electric and Backup Generation under Electricity;
- removing all commodities except Steam, Delivered Fuel, Electricity, Natural Gas, and Chilled Water; and
- replacing Steam records with units of “days.”

Internet Naval Facilities Assets Data Store

iNFADS provides several key metrics, including square footage on which the energy reports and charting are based. Also aligned with the same filter that the Goals Package applies to iNFADS data, NSGEM includes only type 2 facilities (which are roofed structures that are suitable for housing people, materials, or equipment and that provide a degree of protection from the weather) and removes all vacant, disposed, public-private venture (PPV) privatized housing, and non-navy buildings. The filtered iNFADS facility data is based on recommendations from CNIC and NAVFAC headquarters, and the result is intended to more closely align to the facilities being tracked in CIRCUITS UA. Approximately 532,000 records per month are fed from iNFADS into NSGEM.

Defense Utility Energy Reporting Systems

DUERS is updated quarterly, is based on the fiscal year, and includes both water and energy consumption values. This data is reported at the installation level, whereas CIRCUITS reports at the facility level, so CIRCUITS is more widely used for facility-level energy reduction projects. The 2003 DUERS baseline for consumption was established to meet the 2020 installation-level energy consumption reduction goals. Approximately 5,000 monthly records and 277 quarterly records are fed into NSGEM each quarter and added to the totality of DUERS data in NSGEM.

Worldwide Common Installation Picture

The WW_CIP is updated at the installation level into GRX, which is the platform that NSGEM sits on. NSGEM itself uses only the Buildings/Facilities layer but still provides an update of approximately 105,000 features per month to include base layers shown in the Regional Energy Map Books.

Extract, Transform, and Load Process for NSGEM

The ETL process handles the actual data merge and applies the appropriate filters for the business rules outlined in the Goals Package. The ETL populates data in the appropriate tables, and then Python scripts copy these values into the appropriate database tables in the navy environment. The navy environment then implements the indexes and runs automated checks to ensure that everything was transferred properly.

Environment Setup

The basic environment setup that NSGEM uses to run the ETL process ensures that the geospatial analyst has access to appropriate spatial database engine (SDE) geodatabases in numerous environments (development, integration, test, acceptance, and production). This redundancy allows for multiple gateways to catch bugs or data issues prior to pushing to the production environment. Additionally, the geospatial analyst has the following programs installed: SQL Developer, Oracle Client, a text editor (e.g., Notepad++), and an integrated development environment (IDE) for Python (e.g., IDLE, Aptana, or PyCharm). Then the analyst checks out an appropriate branch of the code repository for access to the SQL and Python scripts.

Data Preprocessing

There are multiple steps for preprocessing the data from the various authoritative business systems, which are essentially miniature ETL processes on their own. Data must be downloaded from the various environments and standardized to be usable by the ETL that combines the data into NSGEM-ready formats. Once the SQL scripts are run for each business system data standardization process, they are merged into their appropriate tables for the main ETL process to be run (figure 23.7). The basic steps of the ETL include combining data, creating data indexes, running insert SQL scripts to publish the data to the various environments for testing, and publishing any new or edited map services. Oracle scripts are available for backing up data and code in case of any fatal update errors.

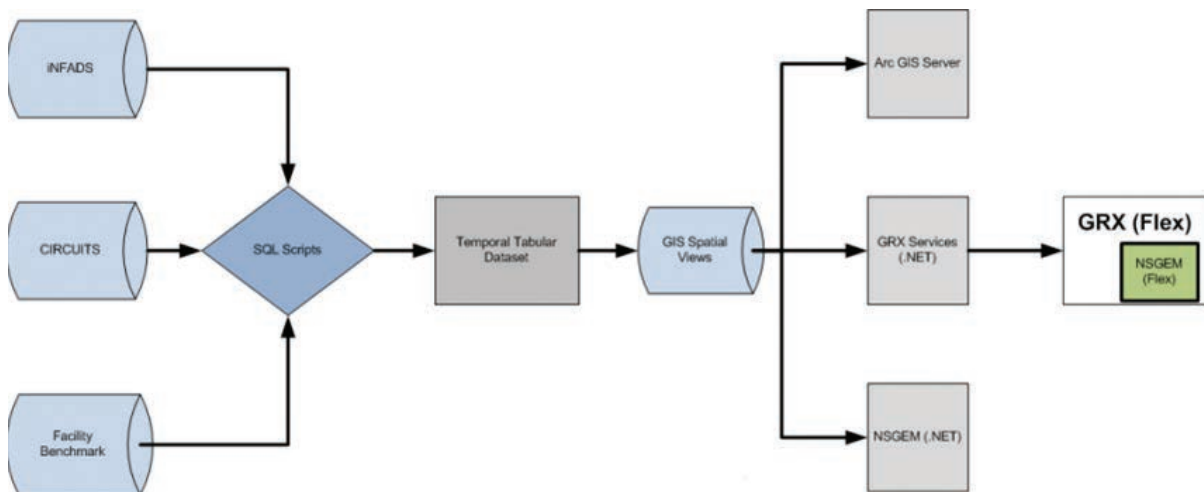


Figure 23.7. Workflow of SQL scripts to incorporate authoritative data into the Navy Shore Geospatial Energy Module. Courtesy of CNIC Energy Program.

Gap Analysis

At the inception of NSGEM, once the authoritative data systems were identified, the database was constructed, and ETL was enabled, gap analysis was initially performed to identify disparities between the main data sources: the navy's iNFADS real-property database, the CIRCUITS utility allocation and billing system, and the GeoReadiness worldwide geospatial data in the CIP (figure 23.8). This effort pinpointed further needs and issues and generated the data quality score shown in the current interface. Data validation and correction are key components, and one of the most challenging aspects, of providing NSGEM functionality. The DAS is calculated at each lens (Navy Enterprise, Region, Installation/Site, and Facility) for the appropriate data reporting authorities to find and correct data discrepancies. Calculating multiple DASs helps ensure that installations work with the most complete data picture, which aids in reaching their consumption goals. Within the Goals Package, iNFADS facilities that are not matched to a CIRCUITS UA facility entry require estimation or “gap filling” of consumption data. Initial identification of CIRCUITS UA data is conducted and allocated to facility data (regardless of whether CIRCUITS UA data is metered, allocated, or estimated). Facilities identified as having no CIRCUITS UA data go through a multistep process to appropriately allocate gap filling of consumption data. The process employs building type medians or building type estimation and applies values evenly across all facilities that have the same significant characteristics.

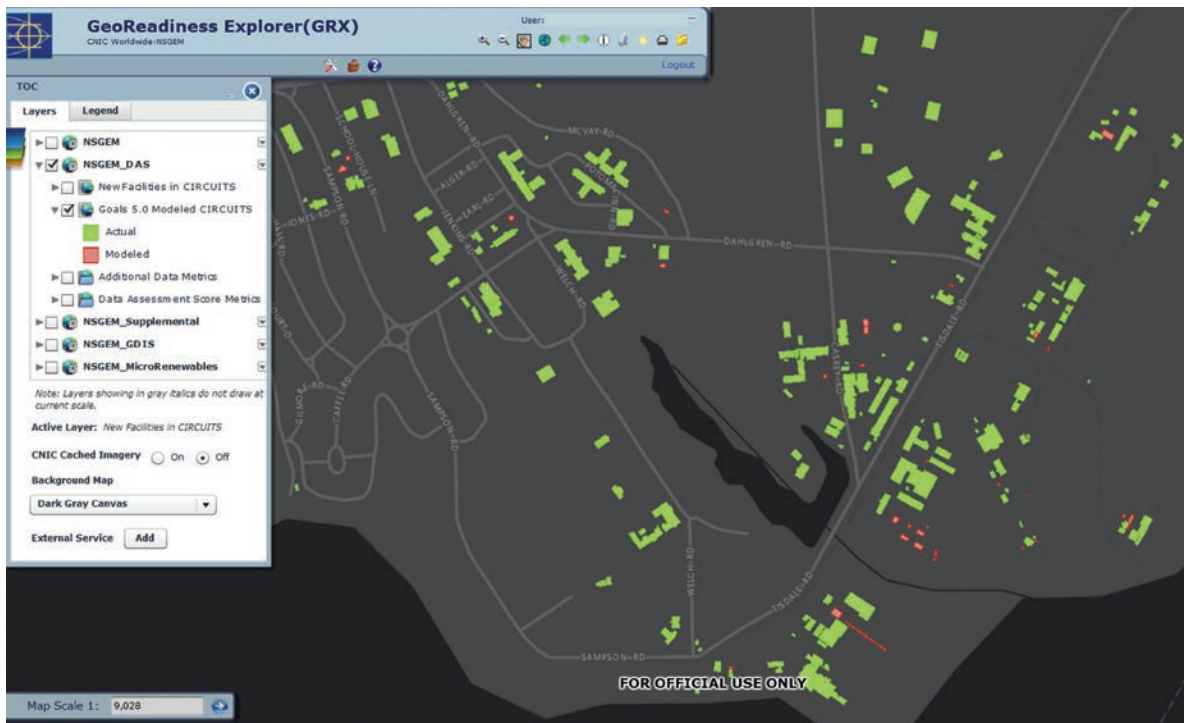


Figure 23.8. Example of facilities that have missing datasets are shown in red, which is a quick and easy way for an installation energy manager to identify data correction needs. Courtesy of CNIC Energy Program.

Standardized Reporting

Using Crystal Reports, NSGEM provides a standardized reporting capability, both as Pre-defined and Custom Reports (figures 23.9 and 23.10). The call process behind standardized reporting allows the Crystal Report document to be read and loaded by the NSGEM reporting web services on the basis of the report configuration. Any subreports, such as a custom report, are loaded into the main report. Generating a report connects the report to the appropriate database in which the NSGEM data is stored, and then applies a record selection formula to each report and subreport to select the relevant data from the database. The report is then exported to a PDF file and written to the file system as a URL-accessible location. Users are able to open the previously written PDF for viewing in a new browser window. Tools used in NSGEM Pre-defined and Custom Reports include SAP Crystal Reports, .NET Framework 4.5, ASP.NET 4.5, Oracle 11g, and ArcGIS for Server 10.1.

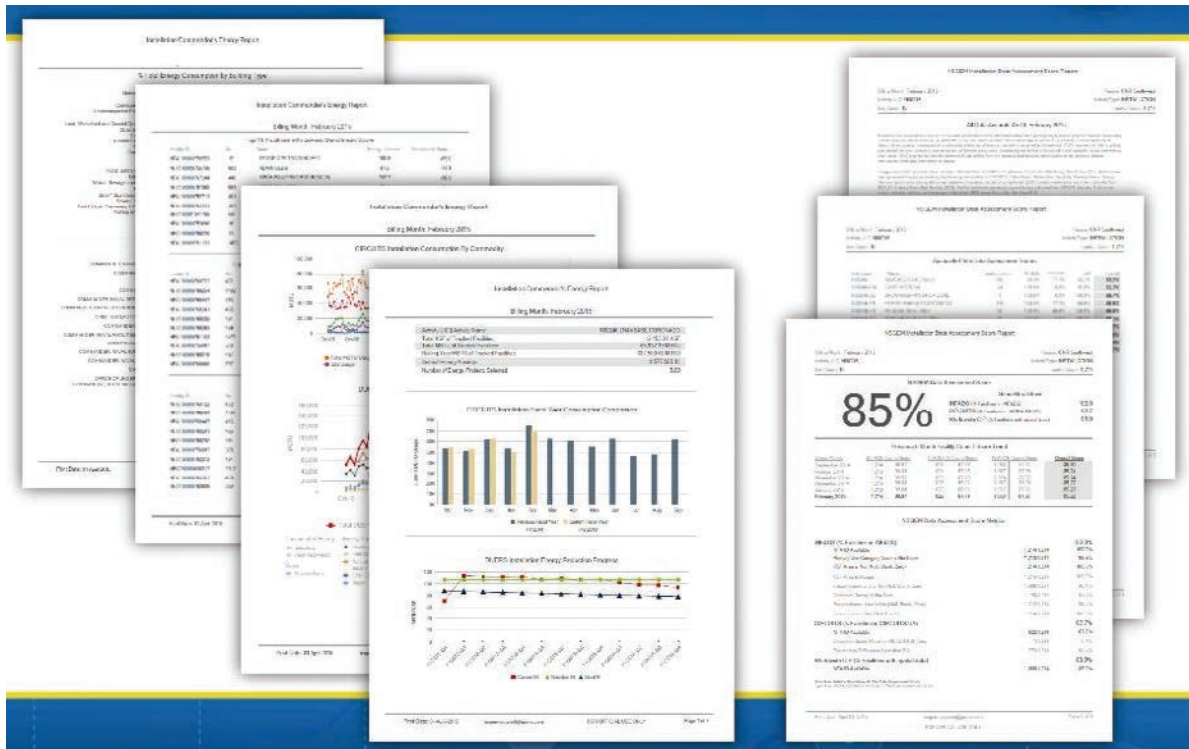


Figure 23.9. Examples of Pre-defined and Custom Reports available in the Navy Shore Geospatial Energy Module as PDFs for a selected installation. Courtesy of CNIC Energy Program.



Figure 23.10. Example of a variety of colorful charts and reports available for a selected Installation. Courtesy of CNIC Energy Program.

Data Assessment Score and Metric Reports

The DAS indicates the completeness, or reliability, of the data available for type 2 facilities (excluding privatized housing) on a scale of 0 to 100. The overall score is calculated by averaging the following three calculations:

- The percentage of facilities for which the following are true regarding iNFADS data: naval facilities asset identification (NFA ID) is available, Primary Use Category Code is not blank, and thousand square feet (KSF) is not null, blank, or zero.
- The percentage of facilities in iNFADS for which the NFA ID has a corresponding NFA ID in CIRCUITS.
- The percentage of facilities in iNFADS for which the NFA ID has a corresponding facility ID in the CIP.

For an Installation to achieve its outlined energy reduction goals, the data must be as complete as possible. An installation's energy reduction progress value can be inaccurate due to many attributes, including, but not limited to, missing or inaccurate values for square footage, consumption values, bill payer, or primary use codes. NSGEM generates a number of Data Assessment Metric reports at the various lenses to assist installation and regional energy managers troubleshoot their data issues and better understand why they may not be meeting their goals, as outlined in the Goals Package.

For the iNFADS data, such reports include Valid NFA (percentage of facilities in iNFADS that have a valid NFA ID), KSF Area Is Not (Null/Blank/Zero) (percentage of facilities for which the value of the KSF Area data element is not null, blank, or zero), KSF Area in Range (percentage of facilities for which the value of the KSF Area data element falls within the range of 20 to 1,000,000 sq ft), Primary Use Category Code Is Not Blank (percentage of facilities for which the Primary Use Category Code data element does not have a blank value), Manpower BSO Is Not (Null/Blank/Zero) (percentage of facilities for which the value of the Manpower BSO [Budget Submitting Office] data element is not null, blank, or zero), Condition Rating Is Not Zero (percentage of facilities for which the value of the Condition Rating data element is not zero), Preponderant User Is Not (Null/Blank/Zero) (percentage of facilities for which the value of the Preponderant User data element is not null, blank, or zero), and the DUERS Code Is Not (Null/Blank) (percentage of facilities for which the value of the DUERS Code data element is not null or blank).

For CIRCUITS data, the following Data Assessment Metric reports are available: NFA ID Matches iNFADS NFA ID, Non-Privatized (percentage of nonprivatized facilities for which the CIRCUITS NFA ID has a matching NFA ID in iNFADS), Occupied Space Matches iNFADS KSF Area (percentage of facilities for which the value of the Occupied Space data element in CIRCUITS matches the value of the KSF Area data element in iNFADS), and Percentage Difference Less than 5% (percentage of facilities for which the percentage difference between the Occupied Space value and KSF Area value is less than 5%).

For the WW_CIP spatial data, the most important Data Assessment Metric report matches the spatial record to the iNFADS asset management record, named NFA ID Matches iNFADS NFA ID, Non-Privatized, which is the percentage of nonprivatized facilities for which the WW_CIP NFA ID has a matching NFA ID in iNFADS.

The Way Ahead

Renewable Energy Goals

In addition to the consumption reduction goals, the navy has outlined renewable energy goals in which at least 10 MW of energy must be generated by renewable sources. Use of renewable energy has many benefits, such as reduction of some types of air pollution and decreased or no greenhouse gas emissions from fossil fuels. Additionally, renewable energy diversifies the US Navy's energy portfolio and reduces dependence on foreign oil. Finally, it adds to economic development by creating jobs in manufacturing, installation, and more (Environmental Protection Agency 2015). The Navy REPO is working closely with the CNIC Energy Program to determine site suitability for renewable technology at the facility level, known as *microrenewables*, as well as larger-scale renewable energy projects on open land. The initial focus is on solar renewable energy power (figure 23.11), but studies of wind and geothermal potential have also been conducted for site suitability.



Solar Resource at Contiguous U.S. Navy Shore Bases Annual Average Solar Photovoltaic (PV) Resource Potential

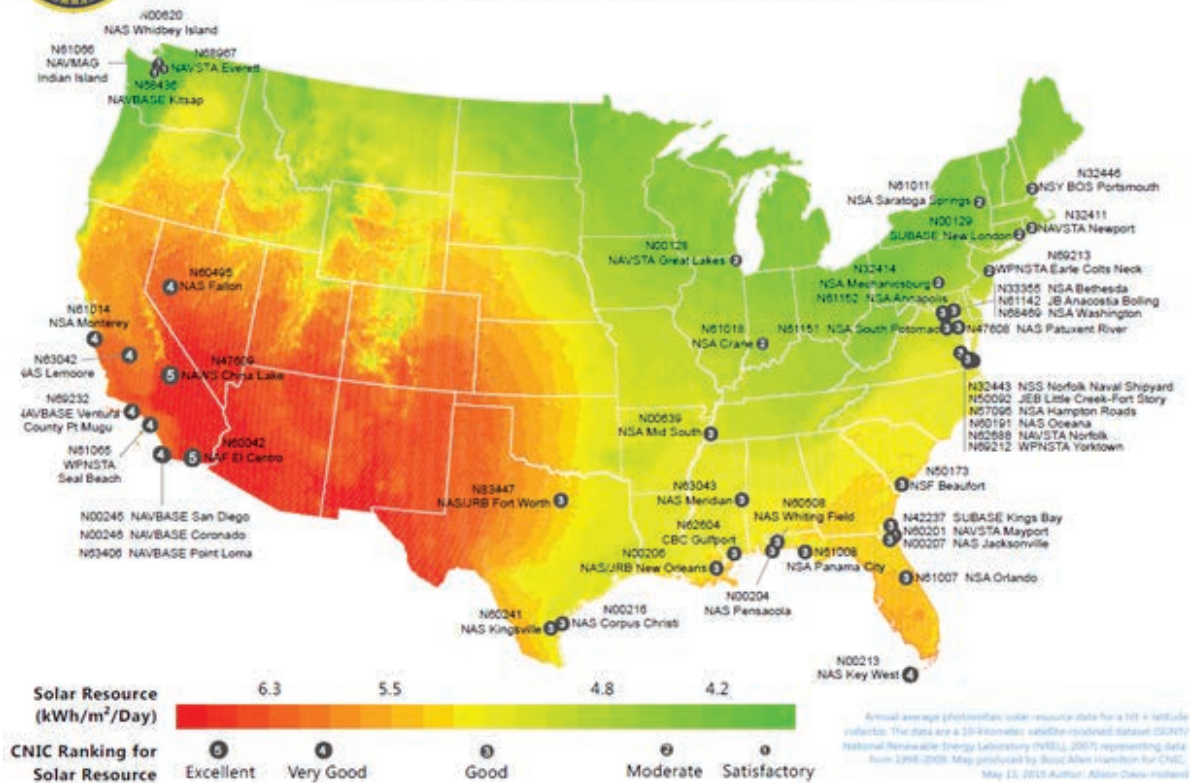


Figure 23.11. Example of National Renewable Energy Laboratory Solar Potential in relation to contiguous US (CONUS) Navy installations. Courtesy of CNIC Energy Program.

Within NSGEM, a Solar Project Potential layer uses real-property data, facility consumption, and resource potential to model distributed solar systems on navy rooftops. Red facilities represent modeled projects that have negative net present value (NPV), and green facilities represent modeled projects that have positive NPV (figure 23.12). In addition to solar project potential, other factors taken into account for site suitability include, but are not limited to, rooftop size, angle and type, and historical value. Once site suitability is complete, savings analysis is completed for the potential renewable energy type.

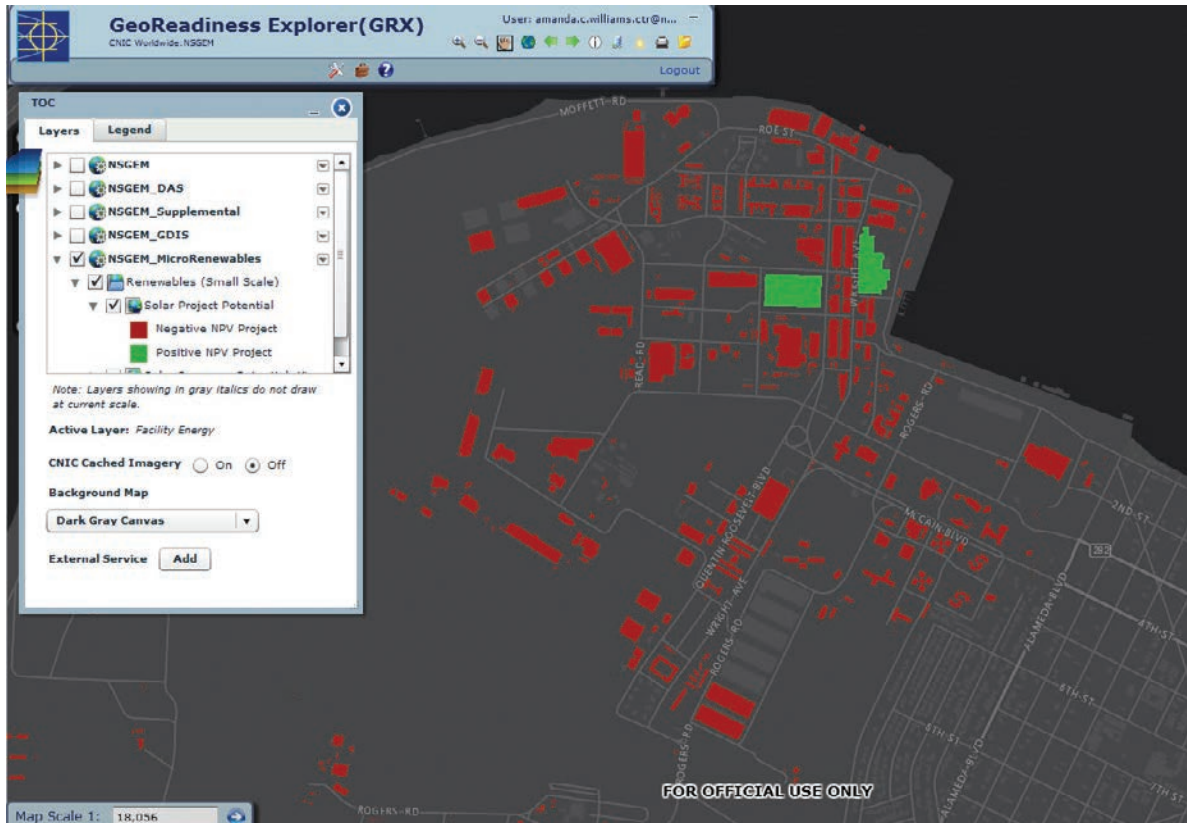


Figure 23.12. Example of facilities that have positive net present value solar project potential (*green*) versus negative net present value solar project potential (*red*). Courtesy of CNIC Energy Program.

Meter-to-Facility Relationship Network

In 2009, President Obama announced the American Recovery and Reinvestment Smart Grid projects to increase the reliability, efficiency, and security of the US electrical system; to encourage consumers to manage their electricity use; and to reduce greenhouse gas emissions while allowing for integration of all clean energy sources into the energy grid. Advanced Metering Infrastructure (AMI) is an integrated system of smart meters, communication networks, and data management systems that enables two-way communication between utilities and customers (US Department of Energy Smart Grid 2015). For the navy's use, AMI potentially enables better data and streamlines data collection, and may lead to a more precise understanding of energy consumption issues to be addressed at a given facility. As part of the navy's AMI initiative and Smart Grid implementation, NSGEM has incorporated the meter-to-meter and meter-to-facility relationships generated from tabular data and displayed as map layers (figure 23.13).

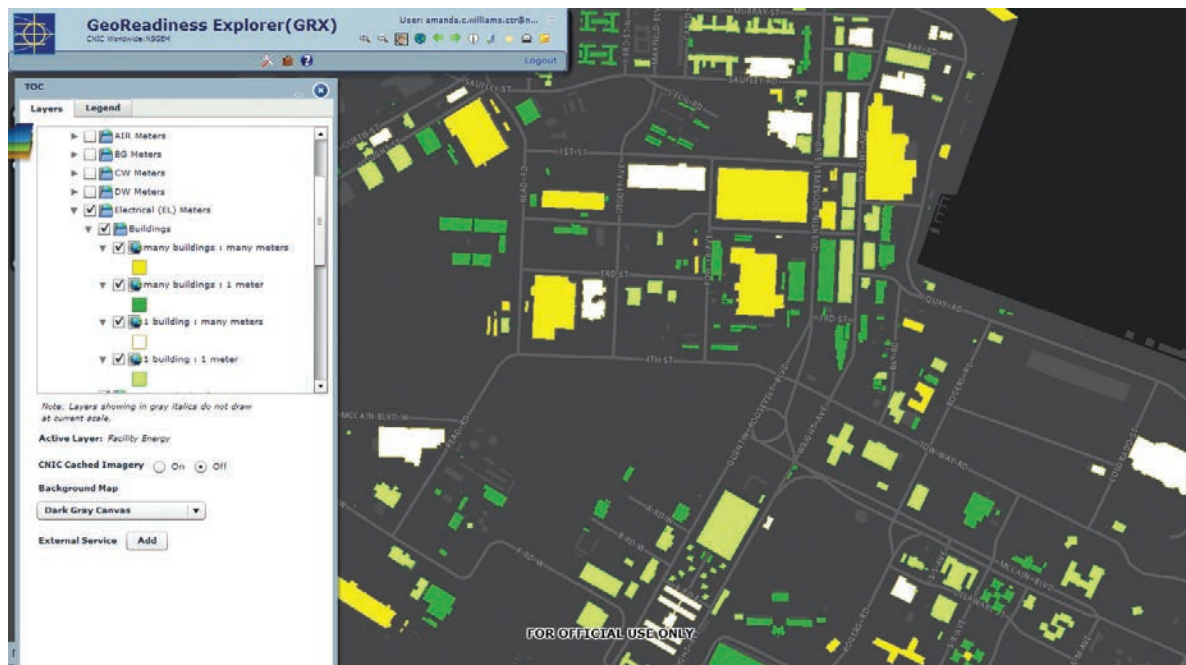


Figure 23.13. The Graphical Data Input System meter-to-facility relationships are depicted in the Navy Shore Geospatial Energy Module by commodity using unique symbology based on relationship type. Courtesy of CNIC Energy Program.

At the most basic level, the tables list meter numbers and facility numbers that can be linked to the real-property records in iNFADS by a unique iNFADS ID. These relationship tables include not only standard hand-read meters but also “smart meters” that can read consumption information in 15-minute intervals. The smart meters will be tied into the CIRCUITS reporting system so that utility allocation can be replaced with real-time consumption data and potentially provide better accuracy and detail. In addition to understanding meter and facility relationships, the mapping of this data will also highlight facilities that currently receive allocated consumption from CIRCUITS UA, which may lead to the installation of more smart meters on facilities.

Direct Data Feeds

The most challenging effort for NSGEM is live linking directly into the authoritative data systems, such as iNFADS, CIP, DUERS, and CIRCUITS. These data systems are continuously updated, so at any given time NSGEM can be out of date. NSGEM is updated monthly because of the complex ETL process and required Naval Facilities Information Technology Center (NITC) outage security protocols. The data used in NSGEM is also used to update the Goals Package and eROI tools, so the CNIC Energy Program as a whole must be in sync across all products. A web service that directly links into the various databases in which the ETL can be run at any given time without an NITC outage is the ideal scenario. However, this scenario is also the most complicated and challenging in trying to align database systems within the various NITC environments. NSGEM aids cross communication between multiple authoritative data systems, beyond aligning data requirements across these systems. With the support of the authoritative systems and stakeholders, NSGEM can use materialized or replicated views of the databases to refresh the data on demand via the ETL. If there are no changes to the database schemas, NSGEM can achieve earlier data updates and remain in closer alignment with the authoritative data systems.

Conclusion

The US Navy is mandated to address the issues of rising costs, increased demand, securing energy, and protecting the environment. CNIC is geospatially enabling the navy's energy program. Geospatial capabilities are changing the way the navy does business, through collaboration, innovation, communication, and performance. Meeting the navy's mandates for energy consumption reduction and integration of renewable energy sources, NSGEM is a pioneer capability on which other facility-level modules, such as potable water or other utility infrastructure systems, can be based.

Currently, NSGEM is a unique, nontraditional, repeatable process, as a geospatial module that assists solving the business problems within the navy program. The navy is leading the effort to integrate GIS technology as a standard business process tool. NSGEM allows for the standardization of processes and provides actionable information that allows the navy to integrate and amplify the knowledge of the energy program across the entire navy enterprise. The navy achieves this integration by assimilating large authoritative data sources, highlighting data gaps, and creating standardized reports. With this information, the navy has a better understanding of total energy consumption, thereby allowing focused efforts down to the facility level to target consumption reduction activities. NSGEM also takes this data convergence to another level by incorporating renewable energy-focused project potential with planned or existing utilities, providing a comprehensive big picture of the entire CNIC Energy Program.

The US Navy CNIC Energy Program is paving the way for other large entities to also meet the federal energy mandates, which results in cost savings. The program is a leader in energy independence and sustainability initiatives. This, in turn, will allow the navy to achieve the established objectives of addressing rising costs and increased energy demands, providing for energy security and protecting environmental resources. All these issues combined will allow for a more efficient and better-prepared navy force.

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Afterword

Except for overfishing, the biggest impacts on the world ocean come from human activities on land, particularly the kinds and amounts of energy we use and the ways we grow and harvest our food. Direct degradation and destruction of coastal habitats also take a toll. Although we rarely manage the ocean, we have the opportunity and responsibility to manage human activities on land that affect the ocean and marine life. And each nation has the opportunity and responsibility to manage its activities within its exclusive economic zone (EEZ), the zone from the shoreline out 200 nm.

The United States has the largest EEZ of any nation on Earth, an area larger than the entire land area of the United States and its territories. The US EEZ is filled with resources, both renewable and nonrenewable, and opportunities; and yet it remains largely unexplored. This exploration—and discovery—should be a national priority.

In the near future, humanity will look to the ocean for more food; more shipping and transportation; more energy, both renewable and nonrenewable; more biologically active compounds to produce medicines; more recreation and tourism; and more water, especially fresh water. Even at the present levels of human activity, we are degrading marine habitats and ecosystems—and losing marine life—at an alarming rate. We have the tools to curb these losses, protect marine life, and accommodate human uses to benefit society in ways that are consistent with environmental goals. Two of the most powerful approaches for accomplishing these goals are marine spatial planning, which is a process, and the use of an ever-expanding array of geospatial tools such as GIS.

This book provides numerous examples of what GIS can do and, more important, how to go about doing it. It includes a treatment of marine spatial planning, which can provide a valuable framework for applying a host of powerful geospatial tools. But the book also includes practical methods for classifying vast stretches of seamounts and sediment drainage systems on the ocean floor that encompass critical habitats, shoreline changes that affect the resilience of human communities as well as animal and plant biodiversity, and even strategic geospatial planning tools to reduce energy consumption and alternative energy sources at US Naval bases. I hope that readers are inspired by these efforts and will put the methods into practice to help bring order to an increasingly crowded ocean for the ultimate protection of marine life and for the benefit of human life.

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Jeff Ardron learned GIS in the late 1990s and applied spatial analyses to marine planning processes in British Columbia, Canada. After completing some early analyses (of which he was inordinately proud) and trying to get these projects accepted, he realized that not everyone shared his enthusiasm for spatial analysis tools. Through discussions with other conservation GIS users, he came to see that there were many pitfalls and little guidance for bridging the science/public policy divide. With the Pacific Marine Analysis and Research Association (PacMARA) and University of Queensland, Ardron led the development of the revised Marxan user manual, the *Marxan Good*

Practices Handbook, and a set of training courses that highlight good practices in the use of such planning tools. He currently works for IASS, Germany, as a senior fellow, developing good practices in the transparency of marine resource planning, particularly deep-sea mining. He maintains his involvement with PacMARA as president of the board.

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Cathryn Brandon is currently working on a PhD in marinescape geovisualization, building a coastal and underwater marine environment in a computer gaming engine using real-world spatial data and digital media to inform its creation. In addition to realism, ethics, and interactivity of geovirtual environments, Brandon is interested in environmental psychology dimensions related to mental imagery of underwater marine environments and its relationship to conservation and environmental attitudes, values, and behaviors and how virtual environments might affect this imagery. Her master's research involved a human-computer interaction study on the use of multiuser touch tables for collaborative geovisualization and decision-making in a marine spatial planning context, emphasizing how to measure collaboration in small groups. Brandon enjoys approaching her research from a psychology perspective, which usually underpins her research in some way. Research interests include marine spatial planning, participatory GIS and community mapping, 3D geovisualization, conservation psychology and behaviors, and marine protected areas.

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In 2014, Chris Caldwell became research coordinator of the NOAA Channel Islands National Marine Sanctuary in Santa Barbara, California. His efforts are focused on establishing partnerships and promoting, conducting, and interpreting science aimed at addressing management priorities. Caldwell has been with NOAA since 2000, when he became a John A. Knauss Marine Policy Fellow with the National Centers for Coastal Ocean Science (NCCOS) Biogeography Branch. The branch specializes in mapping the distributions of marine plants and animals to aid decision-makers faced with spatially explicit management decisions. In 2010, Caldwell became the branch chief balancing the branch's efforts on core strengths such as seafloor characterization and science to support coastal zone management with emerging issues of national importance such as renewable-energy development and marine spatial planning. Caldwell obtained a BS in aquatic biology from UCSB in 1996 and an MS in biology from the University of Houston in 2000.

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A BSc in marine biology at McGill University introduced Rosaline Canessa to the fascinating marine realm. But it was during her master's study in marine resource development and protection at Heriot-Watt University in the late 1980s that she discovered the curious intersection between GIS and the marine environment. That curiosity was nurtured during a PhD in the 1990s at the University of Victoria on coastal spatial decision support systems and her subsequent consulting work. Currently, Dr. Canessa is an associate professor in the Department of Geography at the University of Victoria and leads the CORAL Group. Her research focuses on place-based coastal management and the use of spatial technologies, such as GIS and seascape visualization, to support marine planning, particularly in interactive and collaborative settings.

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Sophie de Beukelaer has been with the Sanctuary since 2005 and is responsible for compiling, creating, and analyzing GIS data layers and related tools to augment efforts of MBNMS staff. In

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De Beukelaer holds a BA in natural sciences from New College and an MS in oceanography from TAMU. She focused her graduate research on the deep-sea ecology of the Gulf of Mexico and combined a variety of remote-sensing efforts, including submersibles and side-scan sonar, to identify the locations of chemosynthetic communities on the northern continental slope. De Beukelaer recently completed a two-year NOAA Coastal Management Fellowship with the Shoreline Management Program at the Washington State Department of Ecology to hone her GIS skills and learn more about coastal policy.

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Ian Eland is a photographer who became interested in GIS while studying at the U of R, recently earning BA degrees there in studio art and managerial studies. He was asked to accompany a U of R research class to see the "Bird Islands" of Tetiaroa to document the fieldwork and photograph the methodologies of GIS data collection. In so doing, he discovered a method for GIS software to manage photographs in a new way that not many artists had yet ventured into. After meeting with Professor Tim Krantz, Eland and team devised a plan to combine GIS software and photographic metadata to create a detailed aerial map. The goal was to better understand why birds populate in certain vegetation and how shifting sands affect the spread of invasive species. After assembling and flying a kite-camera rig for a couple of days, the team gathered enough data to start creating the high-resolution aerial map of one of the motus of Tetiaroa, an atoll in French Polynesia. Their ambitions were worthwhile, and the results were shared at the 2014 Esri Ocean Forum, further resulting in Eland coauthoring chapter 21 of this book.

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Rob Fatland works collaboratively on applications of technology to data-driven problems in environmental science at Microsoft Research. His education includes a PhD in geophysics from the University of Alaska, Fairbanks, and a BS in physics from Caltech. He also worked in remote sensing at NASA/Jet Propulsion Laboratory (JPL) for six years. He joined Microsoft Research in 2010 and works with academics to build open solutions in the environmental data space, from sensor deployment to cloud processing with domain emphasis on oceanography. Dr. Fatland built a set of tools to enhance the Worldwide Telescope Virtual Globe, including an online learning/collaborating/sharing website named Layerscape, at <http://layerscape.org>, and a set of developer tools named Narwhal that facilitate composition of complex data-driven visualizations from 30 million time-evolving geospatial data points.

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Zach Ferdaña is the lead Coastal Resilience Program manager for TNC. He supports US and international projects in ecosystem-based management, climate adaptation, and marine spatial planning. He manages the design and implementation of online decision support tools to promote the role of coastal habitats in hazard mitigation, restoration, and resilience planning. As part of the Conservancy's Global Oceans Initiative, Ferdaña provides planning, spatial analysis, project management, and geodesign expertise to the organizations' Coastal Risk and Resilience strategy. He received his degree in environmental studies at the Evergreen State College in Olympia, Washington, with concentration in landscape ecology and marine mammal biology in 1994. He then went on to earn an advanced technical degree in GIS at the University of Washington in 1998. He joined TNC in 2000.

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Laura Flessner first joined TNC in 2012 as a NOAA Digital Coast Fellow working with the Coastal Resilience team to help develop and design decision support tools that enable communities to evaluate the role that coastal habitats play in risk reduction and adaptation. Now she is the spatial analyst for TNC's Global Oceans Team. She provides spatial analysis, database management, web mapping, and outreach/training capacity that supports the Coastal Risk and Resilience strategy. This strategy includes programs such as Coastal Resilience, Mapping Ocean Wealth, Floodplains by Design, and the poststorm Recover, Rebuild, and Restore project. Flessner received her undergraduate degree from Virginia Tech and an MS in coastal management with GIS certification from the University of North Carolina, Wilmington.

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Karen Grimmer has been with MBNMS since 1999 and is responsible for resource protection activities within the agency, leading a team of six. She served as deputy superintendent from 2007 to 2012 and has worked at the Sanctuary in a variety of positions, including Sanctuary Advisory Council coordinator and program coordinator of the Multicultural Education for Resource Issues Threatening Oceans (MERITO). She has over 22 years' experience in marine resource management and oversees the site's marine policy activities, including fisheries-related actions (e.g., essential fish habitat), vessel traffic compliance, lost fishing gear removal, and acoustic impacts, as well as some permitting actions (e.g., desalination). Most recently, Grimmer led a team to establish SESAs within the Sanctuary and worked with fishermen and conservation groups to collaboratively propose boundary modifications for the trawl fishery.

Grimmer grew up in the San Francisco Bay Area and served as the director of education for the nonprofit Marine Science Institute (MSI) in Redwood City, California. Prior to MSI, she worked as an aquarist at Steinhart Aquarium in San Francisco. Karen received her BS in biology from San Francisco State University and her master's degree in education from California State University (CSU), Hayward.

Dr. Greg Guannel

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Greg Guannel is the urban conservation director for TNC in Miami, Florida. Dr. Guannel is an ocean and coastal engineer by training. After receiving his MSc in civil engineering in France and an MS in coastal and ocean engineering at TAMU, Guannel worked as a civil engineer with a sediment remediation and coastal work consulting firm, making sure that rivers and coastlines are beautiful and free of heavy chemicals and biohazards. After receiving his PhD in coastal engineering from Oregon State University, he worked with the Natural Capital Project, designing tools and methods to quantify and value the coastal protection benefits delivered by natural systems to humans. Now, Guannel works to show how nature-based infrastructure and natural systems can help increase the city's resilience, improve the urban community's well-being, and increase biodiversity in and around the greater Miami Metropolitan region.

Dr. Anne Guerry

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Anne Guerry leads the marine work of the Natural Capital Project. She oversees the ongoing improvement and expansion of the marine InVEST tool and coordinates its application in diverse contexts worldwide. Beyond nature's benefits, Dr. Guerry's primary research interests are in community ecology, rocky intertidal systems, and ecosystem-based management. She received her PhD in zoology from Oregon State University, her MS in wildlife ecology from the University of Maine, and her BA in environmental studies and English from Yale University. She has a lifelong love of the sea and believes that making explicit connections between human activities and their impacts on the full suite of nature's benefits can inform management decisions and yield better outcomes for the environment and for society.

Todd Hallenbeck

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Todd Hallenbeck is project coordinator of the West Coast Ocean Data Portal. He graduated with an MS in coastal watershed science and policy from CSU Monterey Bay, where he studied seafloor mapping, benthic ecology, and the application of GIS technology to ocean policy. Hallenbeck completed a two-year West Coast Governors Alliance and Sea Grant Fellowship, in which he worked directly with the California Governor's Office of Planning and Research Natural Resources Agency staff to provide GIS and staff support for California's public process to develop a marine spatial plan for renewable ocean energy. During his fellowship, Hallenbeck also helped spearhead the creation and coordination of a West Coast-wide network of ocean and coastal data managers and users to help increase the discoverability and connectivity of ocean and coastal data and people to better inform regional resource management, policy development, and ocean planning.

Courtney Helen Hann

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Courtney Hann is a Master of Science candidate in the Marine Resource Management Program, which is part of the College of Earth, Ocean, and Atmospheric Sciences at Oregon State University. She earned an honors BA in marine science from UC Berkeley in 2012. Hann's current research focuses on the education and research applications of a citizen science-based mobile application, Whale mAPP, developed by Dr. Lei Lani Stelle and Melo King. She is particularly interested in how Whale mAPP can be applied toward marine mammal research and used as a tool for expanding marine mammal literacy and in how to improve the application to optimize both research and learning outcomes. In addition, Hann is using historical whaling data, one of the first citizen science marine mammal datasets, to study the relationship between sperm whales and seamount geomorphology off the coast of New Zealand. Her background in oceanography, marine biology, and education support her interest in citizen science and marine mammal projects.

Dr. Peter T. Harris

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Peter Harris is a native of the United States and has worked in the field of marine geology for over 30 years. He moved to Australia in 1984 and lectured at the University of Sydney on marine geology and sedimentology and later became a program manager at Geoscience Australia. Since 2006, he has worked as Australia's representative for the United Nations World Ocean Assessment. He has published over 100 papers on seafloor processes and geomorphology, mainly based on data collected from Australia and Antarctica. Dr. Harris's recent work has focused on applications of seafloor geomorphology and GIS for marine spatial planning and conservation. Harris holds a BS in oceanography and geology from the University of Washington in Seattle and a PhD in oceanography from the University of Wales in Swansea, United Kingdom.

Eric Hartge

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Eric Hartge joined COS as a research and curriculum development intern in November 2010 before becoming a research analyst in July 2011 and then the senior research analyst in November 2013. In summer 2015, he was promoted to research development manager. Hartge specializes in organizational management and project portfolio development. He also helps decision-makers plan for a changing ecosystem by advising them on coastal adaptation strategies based on the preservation of natural features. His current projects include a collaborative effort with the Natural Capital Project and Stanford Law School using the spatial analysis tool InVEST to incorporate multiple benefits from natural habitats in decision processes regarding coastal adaptation planning throughout California. In addition, Hartge is developing and implementing a revised project portfolio management approach for COS. He received his MS in environmental sciences and policy from Johns Hopkins University and his BS in marine biology from the College of Charleston in South Carolina.

Dr. Knut Hartmann

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Knut Hartmann has background in applying Earth observation data and spatial analysis to environmental applications. Before joining EOMAP in 2011, he worked in environmental consultancy and research. Dr. Hartmann graduated as a geoecologist in 2007 and received a PhD in natural science in 2010. He manages EOMAP's expert team of coastal mapping and has led several international projects, such as the European Space Agency World Bank Coastal Zone Management project in India.

Dr. Thomas Heege

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Thomas Heege has more than 20 years' experience in aquatic remote sensing and technical consultancy. He has headed the company EOMAP GmbH & Co.KG in Seefeld near Munich, Germany, since 2006. Before founding EOMAP, Dr. Heege worked from 1995 to 2006 as a scientist and project manager at the German Aerospace Centre DLR, where he and his team developed the initial version of the sensor-independent processing system MIP. His passion for lake and coastal water monitoring was also furthered through his employment at the Limnological Institutes of the Universities of Munich and Konstanz, where beginning in 1993 he developed bio-optical models and hyperspectral approaches to mapping submerged habitats and bathymetry. As a remote-sensing expert with experience in interdisciplinary projects around the globe, he is familiar with implementing users' needs in practicable solutions for offshore industries and water agencies. Heege graduated as a physicist in 1993 at the University of Konstanz and Heidelberg and received his PhD in multispectral airborne remote sensing of water quality in 2000 at the Free University of Berlin.

Nuria Hermida Jiménez

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Nuria Jiménez is a technical surveying engineer and engineer in geodesy and cartography. She has over 14 years' experience in marine geomatics, including marine thematic mapping; designing, developing, and maintaining large spatial database systems; and applications and analytical issues in GIS for oceanographic data. She has participated in oceanographic research surveys, including the underwater volcanic eruption of El Hierro Island. Recently, Jiménez has focused on the development of a marine spatial data infrastructure that comprises a metadata catalog, interactive web map viewers, standard map services, and search functions.

Sarah D. Hile

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Sarah Hile is a marine ecologist with NOAA NCCOS, a CSS-Dynamac contract position she has held since 2004. She has an MSc in coastal ocean management from the University of Ulster in Northern Ireland, with a current research focus on the condition of coral reef ecosystems, habitat utilization of reef fish, and management of marine protected areas. Hile is the comanager and quality control monitor of an extensive Caribbean-wide fish metrics and benthic composition database and a field coordinator of Caribbean field missions. Her work includes leading training seminars for field data collectors, ensuring the accuracy of data and metadata housed in a publicly served database, conducting data analyses, and assisting in field mission planning and preparation, as well as generating products and publications. Hile is also involved in preschool and elementary science education and outreach efforts, with a focus on introducing science experiences at an early age.

Dr. Matthew K. Howard

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Matthew Howard is a physical oceanographer with 37 years' experience and training. His interests include data management, informatics, and interoperability. Dr. Howard has been involved with the US Integrated Ocean Observing System (IOOS) since 1998 and served on its Data Management and Communication Steering and Quality Assurance of Real-Time Oceanographic Data Program advisory teams. He is a member of the Marine Metadata Interoperability executive team. He is currently the data manager of the Gulf of Mexico Coastal Ocean Observing System (GCOOS) and a principal investigator in the Gulf of Mexico Research Initiative Information and Data Cooperative. He has been the principal data manager of some of the largest field experiments conducted in the Gulf of Mexico, including the Louisiana-Texas (LATEX), Northeastern Gulf of Mexico (NEGOM), and Mechanisms Controlling Hypoxia (MCH) surveys. Recently, Howard has become active in Gulf of Mexico glider deployments in support of hypoxia studies.

Dr. Stephan Howden

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Stephan Howden is an associate professor in the Department of Marine Science (DMS) at the University of Southern Mississippi (USM). Dr. Howden teaches in the DMS Hydrographic Science academic program, which is one of two programs in the United States that are recognized by the International Federation of Surveyors/International Hydrographic Organization/International Cartographic Association International Board at the Category A level. He also operates the Central Gulf of Mexico Ocean Observing System (CenGOOS), at <http://www.cengoos.org>, and since 2003 has been involved with GCOOS, for which he presently serves as a member of the board of directors.

Dr. Christopher (Chris) F. G. Jeffrey

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Chris Jeffrey is a senior science professional and GIS practitioner with 20 years' experience in conducting and managing scientific research in coral reef ecosystems and communicating information to promote sustainable use of natural resources through minimal human impacts to the environment. He has designed, planned, and implemented field-based research programs to sample marine populations of interest, analyzed information to quantify spatial patterns in fauna and flora, and evaluated the status and condition of coastal marine ecosystems (e.g., coral reefs, sea grasses, and mangroves) in the US Caribbean. Dr. Jeffrey holds a PhD in ecology and an MS in conservation biology and sustainable development from the University of Georgia. In 1999, he was named a John A. Knauss Marine Policy Fellow with the NOAA NCCOS Biogeography Branch. He is employed by CSS-Dynamac and currently manages a team of NOAA-affiliated scientists who apply science and technology to create a healthier, safer, and environmentally sustainable future.

Dr. Chris Jenkins

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Chris Jenkins has research interests in the large-scale patterns and processes of ocean-floor materials, both geogenic and biogenic. An Australian from the beaches in Sydney, he holds a BSc Hons in earth sciences with mathematics and computing from Sydney University and a PhD from Cambridge University (UK) in stratigraphy and paleontology. After experience in teaching, research, and industry, he rejoined Sydney University for long Pacific and Indian Ocean geophysical explorations. Dr. Jenkins's current research specialties include sedimentology, sonars and geoacoustics, biological seafloor, computational semantics in data, and numerical modeling. His present appointments are at the Universities of Colorado and Adelaide, while directing the major international project dbSEABED, which supplies numerous ocean research and management programs with essential seabed (seafloor) data.

Dr. Ann Elizabeth Jochens

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Ann Elizabeth Jochens is a research scientist in oceanography at TAMU. Her principal interest is development of integrated, comprehensive ocean observing systems through partnerships. She came to physical oceanography as a mathematician and attorney with extensive experience in environmental, safety, and permitting in the oil and gas and minerals industries. She was a principal investigator and project manager for 15 studies funded for over \$35 million. These multi-institutional, interdisciplinary studies focused on the circulation, water properties, and habitat over the Texas, Louisiana, Mississippi, Alabama, and Florida continental shelf and slope and the deep waters of the Gulf of Mexico. She participated in an ocean observatory project off Oman and was the US World Ocean Circulation Experiment Project Scientist. Since 2005, Dr. Jochens has held leadership positions and served as the first executive director of GCOOS-RA, a partnership of government agencies, academic and research institutions, and private industries that is working to develop a comprehensive ocean observing system for the Gulf.

Chad King

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Chad King has been with the Sanctuary since 2002 and is responsible for the collection, analysis, and dissemination of spatial data for SIMoN and MBNMS. This data helps integrate past and present monitoring programs within the Sanctuary and is the foundation of decision-making tools such as interactive maps that are made available to the general public. He is a NOAA dive master and an active participant in subtidal research, including kelp forest monitoring and underwater photography and videography. Additionally, he produces short outreach films and significant content for the Sanctuary Exploration Center. King was instrumental in developing SeaPhoto, an iOS app that features imagery and life history content of MBNMS. King has an MS in marine science from Moss Landing Marine Laboratories, and his academic research focused on kelp forest ecology and subtropical ecological dynamics and genetics in the Gulf of California.

Melodi (Melo) King

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Melo King stumbled on GIS after abandoning a graduate program in chemical engineering and quickly recognized it as a natural framework for pursuing a career she was passionate about. After a year of side projects in mapping public art and water systems, she earned her MS in GIS from the U of R. There, she began building Whale mAPP, a GIS-based citizen science project that encourages participation in marine mammal research. With her company, Smallmelo, King combines her degrees in engineering and GIS with her research in user experience/user interfaces, design, and programming to help organizations collect and interact with spatial data.

Dr. Barbara Kirkpatrick

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Barbara Kirkpatrick is the executive director of GCOOS-RA and a research scientist in oceanography at TAMU. Prior to joining GCOOS-RA, she investigated the human health impacts of harmful algal blooms (HABs) and created the Beach Conditions Reporting System to provide beachgoers with near real-time information for informed decision-making. Dr. Kirkpatrick is the cochair of the National HAB steering committee and also the cochair of the Interagency Ocean Observation Committee (IOOC) Glider Task Team.

Dr. Shinichi Kobara

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Shinichi Kobara is a marine geographer and certified GIS professional (GISP) with over 12 years' experience in geospatial analysis and the development of map applications. He has a BS and MS in bioengineering from Soka University in Japan and a PhD in geography from TAMU. Dr. Kobara has applied geospatial theory and GIS to studies in the marine environment, specifically in prediction of reef fish spawning aggregations. His current research interests include the analysis of geospatial environmental information for natural resource management. He is currently involved in developing web map products for GCOOS.

Dr. Peter Kouwenhoven

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Peter Kouwenhoven (1959–2015) was a senior scientist with CLIMsystems. He started his career more than 20 years ago with Resource Analysis in Delft, the Netherlands, as an international consultant bridging the gap between science and policy. He worked on planning issues in the Netherlands and many other countries with an integrative approach that usually included work on environmental change and often climate change. Dr. Kouwenhoven brought a wide-ranging expertise and experience to his endeavors. He worked on models on every scale (from microscopic organisms to global), many topics (e.g., ecology, hydrology, sedimentation, pollution, eutrophication,

air traffic, economy), applications (e.g., risk assessment, adaptation options, planning), and time scales (current, through midterm and long term). He developed modeling tools (science, technology, engineering, and math, or STEM, for differential equations and rapid assessment process, or RAP, for qualitative modeling) and applied these tools in his work with various stakeholder groups (local communities, experts, decision-makers). Internationally, Kouwenhoven was involved in GEO (Global Environmental Outlook) from the United Nations Environment Programme (UNEP), as well as CAN (Collaborative Adaptation Network). He worked in more than 30 countries, including New Zealand, the Netherlands, Brazil, Nigeria, Canada, India, Bangladesh, Uzbekistan, China, Kazakhstan, Kyrgyzstan, the Philippines, Vietnam, Fiji, the Cook Islands, Samoa, Vanuatu, Nauru, Kiribati, Tonga, Tuvalu, and Mauritius. This experience gave him a unique perspective on global climate change, which he continually drew on for his consultancy and training work with CLIMsystems.

Kouwenhoven held a PhD in environmental management from the Technical Environmental Management Group in the Department of Chemical Engineering at the University of Twente in Enschede, Netherlands. He held an MSc and BSc in biology from the University of Leiden, Netherlands. He also held certificates in computer science, communication training, and small business management. Kouwenhoven was an associate member of the New Zealand Planning Institute and an adjunct associate professor in the Climate Change Program at the University of the Sunshine Coast in Queensland, Australia. He will be sorely missed by GIS and climate change colleagues around the world.

Dr. Tim Krantz

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Tim Krantz is a professor in the Environmental Studies Program at the U of R, working in French Polynesia since 1993, primarily based out of the Gump Research Station on nearby Mo'orea Island. Between 1993 and 2003, he led six research classes to see the "Bird Islands" of Tetiaroa; hence his surprise when, upon bringing a small U of R research class to Tetiaroa in May 2011, he noticed how narrow the channel had become from when he was last there in 2003. The team completed a GPS shoreline delineation at that time and then returned in 2014 to complete the kite aerial photogrammetry of Tahuna Iti, which is the subject of chapter 21 in this book. Dr. Krantz holds a PhD from UC Berkeley, an MA in Latin American studies from Stanford, and a BA in ethnobotany from the U of R.

Andy Lanier

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Andy Lanier is a coastal resource specialist with the Oregon Coastal Management Program, a division of the Oregon Department of Land Conservation and Development. He is a graduate of the marine resource management master's degree program at Oregon State University, where he also earned his GISP certificate. Lanier joined the department after completion of a two-year NOAA Coastal Management Fellowship, in which he worked toward the creation of an ocean GIS database for use by state agencies and community interest groups. Lanier is currently participating in the West Coast Governors Alliance on Ocean Health as cochairman of the West Coast Ocean Data

Portal Action Coordination Team, working to improve timely access to relevant coastal and ocean data on the West Coast. He has also been active within the Oregon coastal and marine spatial data networking community.

Alie LeBeau

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Alie LeBeau is the education program manager at the Aquarium of the Pacific. She serves as primary project manager for many grant-funded projects within the Education Department, including the Institute of Museum and Library Services-funded Spherical Interpretation and Technology Integration staff professional development project and annual Boeing Teacher Institute. She has a background in elementary education, outdoor education, and community partnerships. Within the department, LeBeau facilitates teacher professional development offerings, manages program staff, develops strategic partnerships, and manages program budgets. She holds a bachelor's degree in biology and education from Earlham College in Richmond, Indiana.

Dr. Jennifer Lentz

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Jennifer Lentz is an education specialist at the Aquarium of the Pacific. She joined the Aquarium's Education Department in April 2013 as a Marine Science Fellow. Dr. Lentz first encountered GIS in 2004 during a summer internship, studying the home range and habitat preferences of eastern box turtles. Her doctoral research focuses on developing geospatial analytical protocols that can be applied in the study of coral health. Her work at the Aquarium uses GIS to develop interactive ways to connect people of all ages to marine science and the ecology of the surrounding world. Lentz holds a BS in environmental science from Hamilton College in Clinton, New York, and a PhD in oceanography and coastal sciences from Louisiana State University, Baton Rouge.

Yinpeng Li

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Yinpeng Li is a senior climate scientist with CLIMsystems. He worked as a climate change science researcher for the International Global Change Institute (IGCI), New Zealand, and the Institute of Atmospheric Physics, Chinese Academy of Sciences. His main expertise is climate change integrated assessment model development. He developed a dynamic vegetation model (DVM) and food and water security models and tools for Food and Water Security Integrated Model System (FAWSIM) and SimCLIM. He is coordinating an Asia Pacific Research Network project on water and food security integrated assessment model development for northeast Asia, including China, Mongolia, Russia, and New Zealand. Li was involved in the development of an Atmosphere Vegetation Interaction Model (AVIM). National and international peers have recognized AVIM, and a series of papers have been published. His research interests also extend to climate risk analysis, biocarbon sequestration assessment, data analysis, and vegetation ecology.

Amy Lyle

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Amy Lyle is a Planner III in the Comprehensive Planning Department at the Sonoma County, California, Permit and Resource Management Department (PRMD). She has been with PRMD since 2005. Her work includes healthy communities planning, overseeing the Countywide Climate Action Plan and Aggregate Resources Management program, transportation planning (including bicycle and pedestrian), specific plan development, water conservation policy, and tribal relations. Lyle was a team member for the General Plan 2020 update. She holds BAs in environmental studies and planning and in political science, both from Sonoma State University.

Miles Macmillan-Lawler

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Miles Macmillan-Lawler is a marine scientist from Australia who works in marine habitat mapping and marine spatial planning. In his early career, he studied the conservation genetics of the endangered spotted handfish. He quickly moved out of the lab and into the field where he worked on a range of marine habitat mapping projects around southeastern Australia. From there, he transitioned into marine spatial planning, working on the design of the Australian Commonwealth Marine Protected Area Network. In 2012, Macmillan-Lawler moved to Norway to take a position as programme leader for marine spatial planning with GRID-Arendal. At GRID-Arendal, he has worked on a range of projects, including the creation of the first digital global seafloor geomorphic features map (<http://www.bluehabitats.org>) and work focusing on building capacity for marine spatial planning with developing countries and small island states.

Paul Manson

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Paul Manson is a PhD student in the Public Affairs and Policy program of the Hatfield School of Government at Portland State University. He is also a fellow in the National Science Foundation-funded Integrated Graduate Education and Research Traineeship (IGERT) in Ecosystem Services for Urbanizing Regions (ESUR). His academic work is divided between scholarship on the role of models, spatial tools, and technology in participatory government efforts and applied practitioner support through participation in regional environmental planning processes. Recent efforts include development of spatially assisted public participation tools for ecosystem services planning in Nevada. This effort supports a local government policy of “no net loss” of ecosystem services. Other research includes Bayesian inferential modeling for marine ecosystem service functions through a National Oceanographic Partnership Program (NOPP)-funded project in partnership with Oregon State University. This project is developing a methodology to manage uncertainty in science and divergent stakeholder opinions. He also recently coauthored a Transportation Research Board report on the development of ecosystem service-based crediting methods to better inform transportation decisions and measure progress. Manson holds a BA in anthropology from Reed College and an MPA from Portland State.

Molly Melius

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Molly Melius joined COS as a law and policy early career fellow in November 2013. Melius received her BS from Georgetown University and her JD from Stanford Law School, where she worked extensively in the Environmental Law Clinic. Before joining the COS team, Melius was an attorney at Bradley Arant Boult Cummings in Nashville, Tennessee, in the Real Estate, Environment, and Natural Resources group. She advised clients on a variety of environmental issues, including water and air permitting and compliance, chemical handling and storage, contaminated property acquisitions, and wastewater treatment. Melius's practice also focused on land-use law, including defending regulatory takings claims on behalf of municipalities and helping private-sector clients navigate the local land-use planning process. Before law school, Melius worked as a program associate at Forest Trends, an environmental nonprofit in Washington, DC. At Forest Trends, she promoted sustainable forest management through market-based conservation incentives, such as carbon trading and biodiversity offsets.

Dr. Steven D. Moore

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As director of the Center for Spatial Studies at the U of R, Steven Moore strives to make spatial thinking, analysis, and decision accessible to as many learners as possible. By pursuing this goal, he hopes to improve science literacy, better equip kindergarten through college students to succeed in STEM courses and careers, and empower citizens to make better choices for themselves and their planet. Dr. Moore expresses this vision in directing the research and instructional support activities of the Center for Spatial Studies, which serves faculty and students across campus. A recently awarded National Science Foundation grant will evaluate curricular materials designed to improve the spatial thinking, computational, and mathematical skills of K–5 students.

Prior to his position at the U of R, Moore served as executive director of the Center for Image Processing in Education in Tucson, Arizona. While there, he served as principal investigator on 19 federally and privately funded science education projects focused on using digital image analysis, GIS, and other computer-based visualization technologies for student learning in grades 5–12, as well as college. He received his BA in biology from Southern Illinois University, an MBA in human resource management and accounting from the University of Illinois, and a PhD in renewable natural resource studies and sociology from the University of Arizona.

Dr. Ruth Mullins-Perry

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Ruth Mullins-Perry is a marine scientist specializing in physical and biological oceanography, ocean observing, and ocean management and policy. Dr. Perry earned her PhD in oceanography from TAMU. Her dissertation research focused on understanding the physical processes driving coastal hypoxia formation on the Texas coast and incorporated the use of real-time ocean observing systems, remote sensing, and GIS statistical modeling to quantify area and identify spatial and

temporal trends of hypoxia in the western Gulf of Mexico. She joined GCOOS as a postdoctoral research associate. Her work focused on incorporating GIS into oceanographic applications, including the statistical mapping of coastal environmental hazards and ocean observing operations, such as profiling gliders and buoys, and outreach and stakeholder engagement efforts, such as K–12 curriculum. Perry recently joined Shell as a marine science and regulatory policy specialist, where she continues to use GIS as an adaptive tool.

Robert Newell

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Robert Newell has a BSc in biology and statistics, an MA in environment and management, and is currently a doctoral student of geography at the University of Victoria, British Columbia, Canada, researching the potential that immersive geovisualization has for supporting coastal management objectives. Newell also works as a research associate of the Canadian Research Chair in Sustainable Community Development program, based in the School for Environment and Sustainability at Royal Roads University (RRU), and as a course developer and instructor in RRU's School of Culture and Communications. Newell has worked on research that includes developing creative and interactive ways of using digital media and online communication to disseminate sustainability research ideas, engage stakeholders and the public in sustainability, and facilitate knowledge sharing and collaborative strategies for sustainable development.

Sarah Newkirk

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Sarah Newkirk develops and implements TNC California's statewide coastal conservation strategies, protecting and restoring coastal ecosystems, promoting coastal resilience to sea level rise, and abating land-based threats to ocean ecosystems. In her 10 years with TNC, Newkirk has directed coastal programs in New York and California, pioneered TNC's coastal resilience approach to multiobjective planning for sea level rise and coastal hazards (<http://coastalresilience.org>), and served as a member of New York state's Sea Level Rise Task Force. Newkirk is both a scientist and a lawyer, and works to integrate cutting-edge science into proactive environmental policy.

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George Raber is an associate professor in the Department of Geography and Geology at USM. Dr. Raber received his PhD in geography from the University of South Carolina in 2003, specializing in GIS. While there, he started working on several projects coupling GIS work with conservation efforts. Since that time, Raber has enjoyed working with TNC on a number of geospatial applications. These efforts include the GIS-based Protected Area Tools, the Climate Wizard, and most recently the Coastal Resilience Program. His research interests are primarily focused on land-cover analysis and terrain modeling using remote sensing, as well as spatial modeling in GIS.

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Rebecca Schaffner began using GIS to support mapping of harmful algal blooms in New York and California, first while completing her MS at the State University of New York (SUNY), Stony Brook, and later as a research technician at the University of Southern California. From there, she moved on to the Southern California Coastal Water Research Project (SCCWRP), in Costa Mesa, California, where she collaborated as a GIS specialist on many different marine and aquatic research projects, including regional surveys of the Southern California Bight and mapping of riverine and wastewater discharge plumes. Schaffner has recently returned to the East Coast to work for the Maine Department of Environmental Protection as a GIS coordinator.

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David Smith is the spatial instruction manager for the Center for Spatial Studies at the U of R. His personal and professional goals include engaging and influencing the next generation of spatial thinkers. He has the privilege of working directly with many of the university's faculty and students in applying geospatial reasoning in their research, classroom, and capstone thesis projects. He works closely with faculty on planning and designing innovative curriculum using geospatial technology, including field data collection methods and data visualization. His primary responsibilities include the application of sound pedagogical strategies for all spatial learners, independent of their experience or background. Smith focuses on the adoption of spatial thinking and GIS across multiple departments, including the humanities, sciences, and school of business. In addition, he teaches introductory GIS courses and conducts periodic workshops on a variety of GIS-related topics, including desktop and web GIS, mobile mapping, GPS, and visualization applications.

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Nathan Strout is currently the director of spatial technology at the U of R and enjoys his role in supporting and promoting geospatial projects across campus and “infusing spatial” into learning, teaching, research, and administration. Strout has been working with GIS at the U of R since 2000 when he started with the Redlands Institute working on the Salton Sea Atlas. During his time as technical manager of the Redlands Institute, he was responsible for the design and development of tools and applications across a diverse set of problems and domains. He earned his MS in GIS from the U of R and has been teaching programming for GIS as adjunct faculty in the MS GIS program since 2008. Strout has a strong GIS and technical background and is passionate about the power that maps and geospatial information have to facilitate better decision-making. To this end, he is deeply interested in the analysis, modeling, and visualization of complex data and providing information and tools to inform and enhance decisions.

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Gregg Verutes leads the training program of the Natural Capital Project, which hosts various introductory sessions and technical workshops throughout the world. His current focus is developing innovative techniques that use maps, games, and problem-based exercises to teach students, scientists, and practitioners about valuing nature. He also serves as a GIS specialist for the marine team working on coastal zone management in Belize and coastal hazard research throughout the United States. Verutes received his MS from SDSU and his BS in policy analysis and management from Cornell University.

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Lisa Wedding joined COS as an early career science fellow in October 2013. At COS, Dr. Wedding works with the Ocean Tipping Points team to quantitatively assess spatial ecological resilience across distinct gradients of human and natural impacts to identify ecosystem-based solutions for managing human activities in the Hawaiian Archipelago. In addition, she is engaged in spatial modeling efforts to support the InCCAP (Incorporating Natural Capital into Climate Adaptation Planning) project. Her work is focused on the valuation of natural systems in protecting coastal communities from climate change impacts along the Central Coast of California. Wedding earned her PhD in geography with a specialization in marine landscape ecology from the University of Hawaii, Manoa, in 2010. She has a special interest in applying a geospatial approach to studying marine biogeographic patterns in support of marine conservation and management.

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A recent graduate of the U of R with a BS in environmental science and a minor in spatial studies (during which time he coauthored chapter 21 of this book), Lucas Wilgers has always pursued the conservation of natural resources with ambition. This path has led to growing experience in field techniques, the effects of environmental impacts, and spatial thinking. Wilgers worked to preserve land and wildlife during his steward internship with TNC's Colorado chapter. He assisted in spatially representing the extent of hydraulic fracturing as the California GIS intern for Fracktracker Alliance. He has recently become the new conservation advocate for The Wildlands Conservancy, a nonprofit in California. In this position, he aims to help preserve wild places and expose people to them, as well as introduce spatial and restoration-based research projects. Wilgers has always had the goal of having an "outdoor office" and believes that land cannot be effectively managed without spatial awareness of what lies within it.

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Dawn Wright was appointed Chief Scientist of Esri in October 2011 after 17 years as professor of geography and oceanography at Oregon State University, where she maintains an affiliated faculty appointment in the College of Earth, Ocean, and Atmospheric Sciences. Wright is a Fellow of the American Association for the Advancement of Science, the Geological Society of America, and Stanford University's Leopold Leadership Program. She currently serves on the National Oceanic and Atmospheric Administration's Science Advisory Board. Wright coauthored the book *Arc Marine: GIS for a Blue Planet* (Esri Press, 2007).