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Introduction to the Special Issue: Marine and Coastal GIS for Geomorphology, Habitat Mapping, and Marine Reserves

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This sixth special issue on Marine and Coastal Geographic Information Systems (M&CGIS) is the first to be based on an organized series of presentations at a conference, the 2008 Association of American Geographers (AAG) Annual Meeting in Boston, Massachusetts, USA. The papers were selected and peer reviewed for publication in this special issue under the theme "Marine Geomorphology as a Determinant for Essential Life Habitat: An Ecosystem Management Approach to Planning for Marine Reserve Networks" (see presentations and resources online at http://marinecoastalgis.net/aag08). The sessions were cosponsored by the Coastal and Marine, Geographic Information Science and Systems, and Biogeography specialty groups of the AAG. The unifying goal of these sessions was to examine critically the growing body of data suggesting that the underlying geology and geomorphology of marine environments dictate the location of critical life habitat for a variety marine species. For example, it is becoming clearer that spawning aggregations of many species of commercially important reef fishes commonly occur at the windward edge of reef promontories that jut into deep water (e.g., Heyman et al. 2007; Heyman et al. 2005). As another example, seamounts serve as attractors for pelagic fishes and as stepping stones for transoceanic species dispersal (e.g., de Forges et al. 2000; Stocks et al. 2004). The broad implications of these findings suggest that geomorphology might be used as a proxy for (or at least help to identify) critical life habitat for marine species and thus serve to advance

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the application of ecosystem-based management (EBM)[1] to the design of marine reserve networks (e.g., Lubchenco et al. 2007; Halpin et al. 2007; Halpern et al. 2008).

With only 5–10% of the world's seafloor 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. Recent advances in technology have increased the array of available tools and the accuracy and speed at which the physical aspects of marine and coastal areas can be mapped. Sea bottom geomorphology and habitat information can be gained through hydrographic surveys with single beam and multibeam eco-sounders and sidescan sonar mounted on boats, submersibles, or remotely operated vehicles (ROVs). Satellite-based remote sensors (e.g., Landsat, QuickBird, and IKONOS) and aircraft-mounted sensors (e.g., LiDAR) have also been successfully used for seafloor mapping. Water column properties (e.g., salinity, temperature, current speed and direction, chlorophyll content, turbidity, nutrients) can be measured directly with boat-based or *in-situ* instruments or remotely with satellite-based sensors (e.g., Aqua, Terra, Seawifs, and Modis). To go along with the physical information described above, ecological information (e.g., species composition, abundance) almost always needs to be evaluated by direct observations and/or with photography and video acquired by ROVs or submersibles. These data are highly variable in space and time so characterization requires multiple observations over various seasons and times. Reliable ecological characterizations therefore can be prohibitively expensive and time consuming and require re-measurement for monitoring. A major goal of our symposium and this focus issue is to illustrate state-of-the-art examples of how researchers have classified, integrated, and analyzed physical and ecological data sources using various algorithmic approaches in M&CGIS to reveal geomorphology as a proxy for habitat. Given the paucity of available data marine habitat data, and the need for rapid and large expansion in marine reserves networks coverage, geomorphological habitat proxies can assist managers in making timely recommendations for high-priority, critical habitats for inclusion within marine reserves.

Analyses of these data provide answers for three fundamental types of questions as follows:

1. What are the locations and shapes of benthic physical forms (e.g., platforms, seamounts, ledges, trenches, or abrupt changes in slope or geomorphic features), under what conditions (e.g., complexity of seafloor, levels of temperature, salinity, characteristics of bottom current regime), and what are the associated species and their uses of these habitats (e.g., feeding grounds, spawning aggregation sites, nursery habitats), as indicated by species composition or abundance over time?
2. What should be the habitat classification categories for a particular region, especially in relation to the adjacent coastal ecology? In reality, how accurate are the classifications derived by quantitative algorithms with regard to where certain species are colonizing? Should these quantitative approaches be standardized somehow?
3. Which habitats and locations are "biological hotspots" and/or areas of essential life habitat for multiple species (e.g., areas of high biodiversity, areas of high marine productivity such as upwelling areas, spawning aggregation sites, important feeding

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[1] Defined by Feeley et al. (2008) as applying "current scientific understanding of ecosystem structure and processes to achieve more coordinated and effective management of society's multiple uses of and interests in the services provided by the ecosystem. EBM does not prescribe a particular outcome; instead, it acknowledge that changing the ecosystem can also change the services it provides."

grounds, nursery or juvenile habitat), and what should be the resulting decisions for monitoring, management, and ultimately conservation?

Articles in this special issue are divided into two main groups, the first focusing essentially on the geomorphology, habitat, and the necessary hydrographic surveying of study areas, while the second group is made up of methodological papers focusing on tools or techniques for classifying or merging data, while also interpreting the geomorphology. The first group of papers begins with a study by Kobara and Heyman that uses marine geomorphology as a predictor of the locations of spawning aggregation sites of Nassau grouper in the Cayman Islands. The paper illustrates that spawning aggregation sites are concentrated at the shelf edges and seaward-most tips of similarly shaped reef promontories that jut into deep water. Wedding and Friedlander use GIS analysis of bathymetric LiDAR (light detection and ranging) data to assess four marine protected areas (MPAs) in Hawaii to determine which geomorphic measures demonstrate important relationships with reef fish assemblage structure, and hence would ultimately serve as the best ecological criteria to guide future MPA design. In spite of variations in habitat complexity between sites and the important relationships between fish distribution and various LiDAR-derived habitat metrics, protection from fishing is found to be the best predictor of fish biomass at all sites. Kracker et al. moves the realm of benthic habitat mapping up into the water column by using hydroacoustic fisheries surveys and subsequent GIS analyses to assess patterns of fish biomass in relation to bottom habitat in the Gray's Reef National Marine Sanctuary on the inner continental shelf of Georgia. Their analysis illustrates that correlations between biota and habitat are better near the seafloor (e.g., proximity to ledges is a good predictor of high biomass in near-bottom regions) than in the water column. Yet overall, the techniques provide an efficient, nondestructive way to quantify fish biomass and associated habitats and will be applicable in other locations.

In the second group of papers largely on methodology, Su et al. move the emphasis into the realm of satellite remote sensing by presenting a method for deriving nearshore bathymetry from IKONOS multispectral satellite imagery using a nonlinear inversion model (the Levenberg-Marquardt algorithm) but with a new, automated method for calibrating the parameters in the model. Their analysis confirms that the derived bathymetry is slightly more accurate and stable for deeper benthic habitats than bathymetry derived from conventional log-linear models. Similarly, Hogrefe et al. present methods for deriving accurate nearshore bathymetry from IKONOS imagery but through a different approach of gauging the relative attenuation of blue and green spectral radiation (the Lyzenga method). They then combine that derived bathymetry with a 10-m terrestrial digital elevation model to create a seamless coastal terrain model of the topography and bathymetry of Tutuila, American Samoa, out to a surrounding depth of ∼250 m. The results have positive implications for defining marine-terrestrial units (MTUs) that span the land-sea interface. This will in turn enable quantitative correlations between upland land use practices and the vitality of downstream reef communities, as measured by coral and fish species composition and diversity. Erdey uses high-resolution multibeam bathymetry from the Point Reyes National Seashore, California, as input to the bathymetric position index algorithm to create initial classifications of seafloor geomorphology. In concert with this, she analyzes backscatter intensity with multivariate statistical tools to delinate sediment textural classes. All methods are encapsulated into a new toolbox using the capabilities of ArcGIS ModelBuilder. Iampietro et al. also use high-resolution multibeam bathymetry and backscatter data, along with submersible and remotely-operated vehicle (ROV) video data at Cordell Bank National Marine Sanctuary (CBNMS) and the Del Monte shale beds of Monterey Bay, California, to produce preliminary species-specific habitat suitability models for eight rockfish species. They use a generalized linear model (GLM) approach to produce the habitat classes, along with supervised texture classification from backscatter mosaics. They find that the GLM is reasonably portable from one location to another; that is, the model for *S. flavidus* (yellowtail rockfish) generated at CBNMS is at least as efficient at predicting yellowtail rockfish distributions at Del Monte. This could still fail in other circumstances where depth holds a strong inverse correlation with the probability of occurrence, or there is a failure to incorporate many other factors such as substrate type, temperature, currents, food availability, predation, and recruitment.

Studies such as Erdey and Iampietro et al. beg the question of whether researchers are ready to move toward a *standardization* of algorithmic seafloor classification approaches. It is useful here to distinguish between classifications that are visual, as opposed to those which are algorithmic. Visual classification relies on local expert knowledge to delineate distinct seafloor features and subsequent classifications of geomorphology by mere visual inspection of the data, by hand and/or with computerized drawing tools that work on an underlain image of a base map. This mode of classification therefore possesses high information content, but may also be subjective, laborious, expensive (if costs for human labor are a factor), and with resolution limited by time or patience. Algorithmic approaches are almost always quantitative, usually automatic or at least semi-automatic, and allow the user to refine the classification at certain stages in the process based on visual observation. This mode of classification, while subject to artifacts, is usually more repeatable, less expensive, and with resolution limited only by the source data.

In further examining various algorithmic approaches, GIS analyses involving quantitative assessment of the shape of the seafloor for habitat characterization have traditionally included slope and aspect of terrain, but also the more rigorous approach of topographic position index (TPI), which measures where a point is in the overall landscape/seascape in order to identify features such as ridges, canyons, slopes, midslopes, etc., and at whatever scale a topographic or bathymetric grid will support. This approach comes from the field of landscape ecology (see the review in Bridgewater 1993), based in part on the ecological land unit/landscape position algorithms of Fells (1995), Anderson et al. (1998), Guisan et al. (1999), Jones et al. (2000), and then Weiss (2001). Iampietro and Kvitek (2002) have championed TPI for the seafloor, Wright et al. (2005) and Lundblad et al. (2006) have extended it a bit further (calling it bathymetric position index or BPI) and codifying it as ArcGIS extension, while Lanier et al. (2007) have introduced an important variation on it (the surface interpretation method or SIM), taking further advantage of the latest 2.5-dimensional capabilities of ArcGIS.

Another important parameter that is calculated is seafloor roughness (i.e., the bumpiness of the seafloor, especially in terms of how convoluted and complex a surface is, and over cartographic map scales that are larger than TPI/BPI). Jenness (2003, 2004) developed a method for calculating a type of roughness called “rugosity,” which is essentially the ratio of study region’s surface area to planar surface area. Ardron (2002) has taken a slightly different approach where flow direction (the number of facets in a grid) and relief variability are combined to produce a “bottom complexity.” Sampson et al. (2008) have recently pointed to still another variation as developed by Sappington et al. (2007), which calculates “ruggedness” by measuring the dispersion of vectors orthogonal to a terrain surface. This method is much less correlated with (and hence distorted by) slope than the rugosity algorithm.

There is also a range of approaches for ecological habitat modeling involving biological data in concert with bathymetry, and extending from the seafloor (using depth, distance to shelf break or shore) up into the water column. These include the aforementioned GLM, generalized additive modeling or GAM, the classification and regression tree or CART, environmental envelope models, canonical correspondence analysis, and Bayesian models, as summarized by Guisan and Zimmerman (2000), adapted for the marine environment by Redfern et al. (2006) and codified in GIS software by Best et al. (2006). It seems that it is always the biology that will provide the greatest challenge.

In assessing these many algorithmic approaches, standardization via scale (regional size of a hydrographic survey) as well as by resolution of the data (size of grid cells) will be key. While we are still far from a *standardization* of algorithmic approaches, our choices of algorithms should be governed by a detailed knowledge of the species of interest and the scale at which that organisms perceive the environment. This can be difficult to track when analyzing multiple species in a marine reserve. Further, while most researchers are using similar sonar systems for gathering multibeam bathymetry and backscatter (e.g., Reson, Kongsberg-Simrad, Acoustic Marine Systems, GeoSwath) the processing procedures for these data are not altogether standardized either (especially for backscatter). In addition, the level of detail in classification is going to depend on whether one also has access to satellite data and subsurface data, in addition to the standard acoustics and the groundtruthing visuals from ROV, submersible, or SCUBA, along with the associated uncertainties in mapping units (e.g., Halley and Jordan 2008). Differences in classifications for shallow versus deepwater regions will also be quite significant, even within the same study area (as pointed out by Lundblad et al. 2006 and Wilson et al. 2007).

These issues were discussed at length during a panel session held as part of the 2008 AAG presentations spawning the submissions to this special issue. Participants reported that efforts in Europe (e.g., Mapping European Seabed Habitats or MESH, a major European Union-funded initiative to harmonize mapping approaches and collate habitat maps in NW Europe, http://www.searchmesh.net) and Australia (e.g., Geoscience Australia; Heap 2006) are moving towards standardizing a classification approach. In the U.S., the Coastal Marine Ecological Classification Standard (CMECS) managed by NOAA and NatureServe (Madden et al. 2005, Madden and Grossman 2008) will be important to consider when identifying marine ecoregions or when mapping from "ridge to reef" (i.e., the connectivity between upland watersheds, intertidal zones, and shallow coastal areas including reefs). This is where offshore classification categories must be integrated with those for wetland and intertidal regions (e.g., Heyman and Kjerfve 1999).

The papers in this special issue shed light on these issues and may lay the groundwork for the future development of a standard decision-tree or matrix of classification approaches, governed by map scale and species. At some point a standard classification dictionary for various settings (e.g., tropical coral reef substrate vs. continental shelf shale beds, etc., deep vs. shallow) and accompanying generic bathymetric, backscatter and biological datasets might be considered as tools for all to work with when testing these various approaches and the GIS extensions that encode them. Further dialogue will be welcomed as to what standard features should appear on a benthic habitat map, not just to aid scientists, but to communicate effectively to managers and policy-making stakeholders in the process of designing or monitoring a marine reserve.

We would like to point out parallel efforts that relate very nicely to the body of work presented in this special issue. The *Marine Geodesy* papers here of course focus on marine GIS and remote sensing aspects of benthic habitat mapping, but a special issue for *The Professional Geographer* (Heyman and Wright, submitted) draws upon the same organized sessions at AAG mentioned at the beginning of this article, with papers not only on the physical and resource geography aspects of benthic habitat, but also on marine policy. A special issue of the journal *Geomatica* (Devillers and Gillespie 2008) is devoted to marine geomatics ("geomatics" being the equivalent term in Canada for GIS, remote sensing, geodesy, and photogrammetry), and featuring papers on the acquisition, processing, management, and dissemination of data from the seafloor, the subsurface, the water column (including pelagic biomass), and the sea surface. Mapping of the Arctic seafloor and the Canadian continental shelf, including benthic habitat, are additional themes, as well as the emergence of ocean sensor networks and ocean observatories. Interested readers should also take note of the annual GeoHab (marine **Geo**logical and biological **Hab**itat mapping) conference (see http://geohab.org), and the recent monograph based on papers presented at this conference since its inception in 2001 (Todd and Greene 2008).

To conclude, we would like to thank all of the contributors to this special issue of *Marine Geodesy* for their enthusiasm and skill in authoring these articles. We thank the many reviewers for their thoughtful insights and care in commenting on and improving all of the manuscripts. Finally, we thank Editor-in-Chief Dr. Rongxing (Ron) Li for his leadership in editing past special issues of M&CGIS, and for his great encouragement and assistance in publishing this one.

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GeoHab Conference Series (marine **Geo**logical and biological **Ha**bitat mapping) – http://geohab.org

MESH, Mapping European Seabed Habitats – http://search.mesh.net