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*Dam*age Control: Restoring the Physical Integrity of America's Rivers

William L. Graf

Department of Geography, Arizona State University

Technological development of America's rivers, including the installation of more than 80,000 dams, has segmented the streams and fragmented their watersheds. A vision for the nation's rivers requires science and public policy that emphasize restoration and maintenance of the rivers' physical integrity to create a great river legacy for future generations. The Clean Water Act mandates the biological, chemical, and physical integrity of the nation's rivers, but researchers and decision makers have paid scant attention to physical integrity. Physical integrity for rivers refers to a set of active fluvial processes and landforms wherein the channel, near-channel landforms, sediments, and overall river configuration maintain a dynamic equilibrium, with adjustments not exceeding limits of change defined by societal values. Rivers with physical integrity have functional surfaces and materials that are susceptible to monitoring and measurement with a set of geographic indicator parameters. Science and policy for the nation's rivers must blend watershed principles with ecosystem concepts, focus on change rather than equilibrium as a defining characteristic of streams, adopt probabilistic rather than exclusively deterministic approaches, and pursue geographic representativeness through hydrodiversity, geodiversity, and biodiversity. The dams that fragment the system also offer opportunities for restoration of some natural characteristics through adjusted operating rules, redesign, and physical renovation, along with the removal of some dysfunctional structures. In the near future, when social values for rivers are likely to revolve around protection for endangered species, economics of flood protection, and dam removal issues, we can enhance restoration efforts by including physical integrity in research agendas, policy decisions, operational rulemaking, and public debate. Our multicentury legacy for future generations can and should be to establish physical integrity for rivers that are as natural as possible, thus insuring that as a system they are parts of the infrastructure for a vibrant national economy, continuing threads of our cultural heritage, and quality natural environments.
Key Words: environmental policy, fluvial geomorphology, riparian ecology, rivers, watersheds.

> Take almost any path you please, and ten to one it carries you down in a dale, and leaves you there by a pool in the stream. There is magic in it.
>
> —Herman Melville ([1851] 1950)

> There is a definite limit beyond which flow-regulation must not be carried lest serious damages befall future generations.
>
> — Gerald H. Matthes (1934)

America's rivers run like living veins through the nation's history, economy, and very psyche. The magic of the rivers has fueled the nation's commerce as well as its imagination, but it is only within the last half century that social opinion and cultural perspectives have changed from viewing rivers as mere transportation routes or sources of commodity water to seeing them as landscapes, hydrosystems, and ecosystems worthy of preservation and restoration. Science has been a powerful handmaiden in each of these perspectives, first supplying the knowledge to assess and use river commodities and services and then, more recently, explaining the fragility of complex riparian ecosystems.

Despite many successes, however, the employment of scientific knowledge and methods in the creation of policy for public waters and the lands associated with them is now exceptionally difficult. Part of this difficulty is that scientific investigators often choose the questions they address for their own particular reasons rather than for the benefit of public policy. Several decades of reductionist, analytical science focused primarily on equilibrium concepts poorly served the needs of decision makers and the general public. The emerging era of multiple uses for rivers, an era that now includes preservation and restoration, requires approaches based on broad synthesis and on concepts that embody broad perspectives rather than mechanistic, limiting viewpoints.

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Any grand vision for the future of America's rivers must accommodate the paradox that our twentieth century legacy is one of technological impacts on streams (primarily but not exclusively through the building of dams), while our stated policy (in the Clean Water Act) for the twenty-first century is the restoration of rivers. In resolving this apparent conflict, citizens, scientists, managers, and policy makers require common conceptual tools for dealing with rivers. This paper generally proposes to enable the creation of a national river legacy by offering a conceptual basis for the most fundamental characteristic of rivers: their physical integrity. The concepts outlined below can be directly incorporated into research, planning, management, decision making, and public debate without new legislation.

Public debate about the future of the nation's rivers and their dams results from the fact that Matthes' (1934) warning of the limits of technology for rivers has become apparent, and that we are the future generation of which he wrote. The past two centuries of intensive technological development of America's river resources have damaged the physical, biological, and chemical characteristics of the streams and their associated landscapes by fragmenting what was once an integrated system (Figure 1; see general critical accounts by Morgan 1971; Berkman and Viscusi 1973; Reisner 1986). In the eastern United States, the creation of numerous canal networks and dams for water storage evolved in concert with the erection of mill dams to power the early phases of the Industrial Revolution. By about 1840, the dams had created an extensively segmented river system with barriers where none had existed previously. In the Mississippi River Basin, fragmentation resulted from navigation locks and dams, which became dominant features of the fluvial system by the mid-1900s. In the Rocky Mountain region and California, water storage and diversion dams for mining and agriculture segmented the rivers beginning in the mid-1800s. The twentieth century witnessed a virtual frenzy of dam building for irrigation, flood control, navigation, and hydroelectric power throughout the nation. During the period from about 1935 to about 1970, the nation's largest dams completed the segmentation of major rivers. In other parts of the world, this segmentation through dam building continues apace: data from Northern Hemisphere showed that almost 80 percent of the rivers in that half of the world are significantly divided by dams (Dynesius and Nilsson 1994).

The social and economic benefits of dams are enormous. The locks and dams on the Upper Mississippi River and its tributaries provided a water-borne navigation system conducting more than 266 billion ton-miles of freight per year and forming a critical link in the nation's bulk commodity transport system, especially for agriculture (U.S. Army Corps of Engineers 1989). Hydroelectric generators associated with dams produce almost 10 percent of the nation's electrical power; in the Pacific Northwest they supply 70 percent (U.S. Bureau of the Census 1995, 601). Dams divert and withdraw more than 100,000 m^3 (100 million ac ft) of river waters each day to supply irrigation for agriculture (U.S. Geological Survey 1998), more than four times the amount used from groundwater. Flood reduction by dams provides some hazard protection for agricultural lands and urban areas throughout the nation. The largest publicly owned

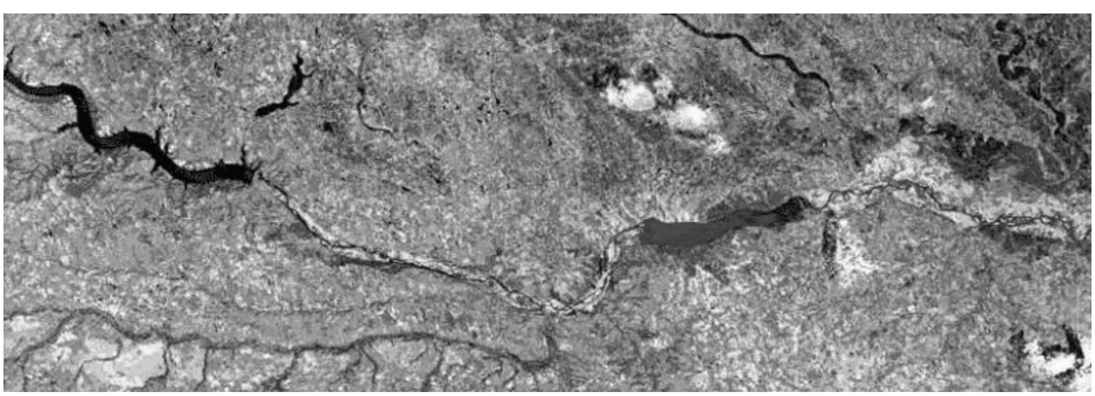

Figure 1. U.S. Geological Survey LANDSAT image of the middle Missouri River in South Dakota showing the fragmentation of the river by dams. North is at the top of the image, which extends about 175 km (110 mi) east-west and about 88 km (55 mi) north-south. The course of the Missouri River enters the view in the upper left corner as a dark, sinuous patch representing the waters of Lake Francis Case, a reservoir ending abruptly at Fort Randall Dam. The river flows eastward in a single thread channel with an inactive flood plain to the dark patch of the waters of Lewis and Clark Lake, created by Gavins Point Dam. Another segment of the stream continues to the eastern (right) edge of the image. The smaller stream entering the west (left) side of the image and joining the Missouri after a sharp northward turn is the Niobrara River of Nebraska. Image courtesy of the U.S. Geological Survey, EROS Data Center, Sioux Falls, South Dakota.

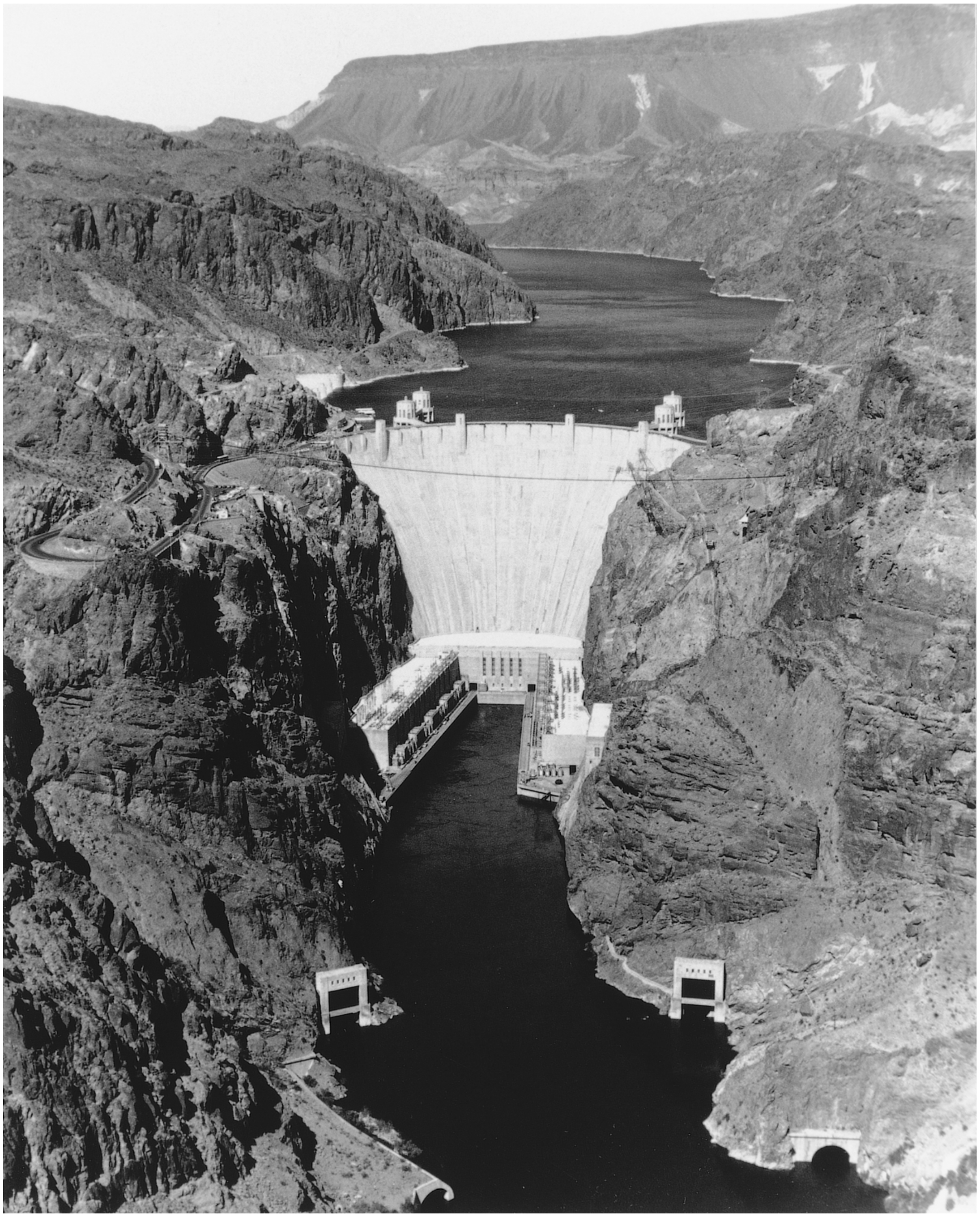

Figure 2. Hoover Dam on the Colorado River at Black Canyon, Arizona and California. The multipurpose structure provides water resources, hydroelectric power, and flood reduction in a service area including more than 20 million people. Photo by E. E. Hertzog, courtesy of the U.S. Bureau of Reclamation.

dams serve multiple purposes and provide benefits to millions of people (Figure 2).

Nonetheless, the environmental response to this extensive and intensive application of technology has led to the disintegration of the nation's river system. More than 80,000 dams currently interrupt the courses of the nation's rivers and are the primary reason for destruction of the natural characteristics of streams. Only after about 1980, when all sites with geotechnical characteristics conducive to dam building had been used, did the consequences of fragmentation became apparent on a broad enough basis to stimulate national attention.

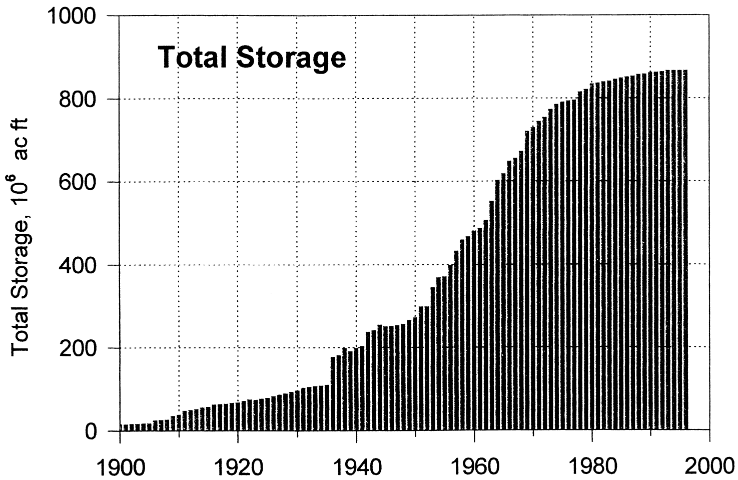

Figure 3. Graph showing the increasing cumulative storage capacity behind dams in the United States, 1900–1996. The most rapid increase was between about 1950 and 1970, with the end of the dam building era by about 1980. Data from U.S. Army Corps of Engineers (1996); figure design from Graf (1999).

This recognition did not surface sooner for at least three reasons. First, dam building and its attending fragmentation of rivers reached its peak only in the 1960s, a decade when a quarter of all the existing dams in the nation were constructed (Figure 3). The fluvial system required some time to register the nature and extent of the impacts which became obvious at the national level only in the 1980s and thereafter. Second, national social values changed to place more emphasis on environmental quality than had previously been the case, so that when the environmental impacts of fragmentation and the effects of reservoirs became apparent, they engendered a newly defined public and governmental response. Finally, the drive to preserve endangered plant and animal species quickly brought researchers and decision makers to the realization that a major reason for species loss was the loss of habitats associated with disrupted rivers. These forces brought about new public expectations for rivers and water resources (Ingram 1990; Graf 1993).

Much of the public and governmental response to environmental degradation of rivers that dams have caused has emphasized river restoration. Governmental and private interests have invested considerable time, energy, and capital to remove some dams, change the operating rules of others to more closely mimic natural flow regimes, alter riparian vegetation through planting, and artificially rebuild river courses to look and behave more like natural streams than mere water conduits (Hunt 1993; Brookes and Shields 1996; Petts and Calow 1996). The guiding principle of most restoration projects is to change existing degraded conditions into ones that are more "natural," but the target of restoration is not defined simply. Massive public investments in restoration now face the primary questions: what is natural for any particular stream, and—given the pervasive effects of dams—what are realistic restoration goals?

The concept of physical integrity is rooted in Section 101 of the Clean Water Act of 1977 (formally titled the Federal Water Pollution Control Act, 33 U.S.C.A. §§ 1251 to 1387), which stipulates that a national priority is the restoration and maintenance of the "physical, chemical, and biological integrity of the nation's waters," including rivers. Further legal standing for physical integrity derives from the Federal Refuse Act of 1899 as modified in Section 404 of the Clean Water Act to authorize the U.S. Army Corps of Engineers to regulate physical changes to the nation's rivers. While federal, tribal, and state governments have emphasized chemical and biological integrity in river management, they have virtually ignored physical integrity. As required by federal regulations mostly administered by the U.S. Environmental Protection Agency, states monitor chemical quality of river waters. They enforce standards related to chemical integrity as defined by acceptable concentrations of various compounds and elements. Biological integrity for rivers is less well defined, though many researchers and managers closely associate it with the maintenance of biodiversity and productivity of aquatic and riparian ecosystems.

I address the following paper to researchers, policy makers, teachers, managers, and citizens who deal with river resource issues. To do this, I briefly explore an agenda of 9 basic concepts:

- fragmentation
- physical integrity
- functional surfaces
- physical indicator parameters
- role of system change
- naturalness
- probabilistic perspectives
- watershed frameworks
- geographic representativeness

Fragmentation

Although the emphasis in the following discussion is on the dysfunctional *fragmentation* of rivers resulting from dams, rivers exhibit a hierarchy of naturally defined geographic divisions: rivers, segments, and reaches. *Rivers*, the largest linear fluvial features, are geographically defined entities with recognized proper names. They begin at the confluence of two significantly smaller streams and usually have obvious termination points in oceans, lakes, seas, dry basins, or confluences with still larger streams. Rivers often either form state boundaries or cross them, so that national administration or decisions derived through interstate compacts are common policy vehicles for them. Rivers are made up of naturally defined *segments* that are tens of kilometers long. The boundaries between segments in natural rivers signal significant changes in river processes or forms, and are often related to geologic structures such as folds or faults, changes in geologic materials, or hydrologic changes such as the inflow of a major tributary. Dams create artificial boundaries and increase the number of segments from pretechnological conditions, and regional management decisions often influence these segments. Finally, segments are made up of *reaches* that are up to a few kilometers long. Physical, biological, and chemical characteristics are similar throughout each reach, forming definable subsystems that are human in scale and often subject to local management and policy decisions.

The natural fragmentation of rivers results from physical or hydrologic divisions that do not prevent the operation of the fluvial system as an integrated whole. The imposition of dams imposed barriers on the nation's rivers that have been effective dividers, separating the physical, biological, and chemical processes in each part of the system from neighboring parts. Dams have segmented the line networks of channels and partitioned the areas of watersheds into successively smaller units that function somewhat independently of each other rather than as an integrated whole.

This physical segmentation has pervasive effects. Dams reset water temperatures downstream from their outlet works, and alter the chemical characteristics of the waters they release. Dams store almost all of the sediment entering their reservoirs, thus starving downstream reaches of their natural sediment supply. Dams disrupt migration patterns for fish and alter hydrologic regimes, causing negative impacts on a wide range of native fish, mussels, and riparian birds, as well as aquatic and terrestrial plants.

The National Inventory of Dams lists 75,187 dams in the United States (U.S. Army Corps of Engineers, 1996; ongoing revisions of the data base indicate that the final estimate will exceed 80,000). Dams included in this accounting are at least 2 m (6 ft) high and impound at least 62,500 m^3 (50 ac ft) of water, or are at least 8 m (25 ft) high and impound at least 18,500 m^3 (15 ac ft) of water (specifications of the Dam Safety Act of 1972, P.L. 92-367). Some additional hazardous structures not meeting these size criteria are also included (specified by Water Resources Development Act of 1986, P.L. 99-662). Every watershed in the nation larger than about 2000 km^2 (750 mi^2) contains some dams, though there is considerable geographic variation in their distribution. The greatest density is in the New England, Mid-Atlantic, South Atlantic, and Lower Mississippi water resource regions; the county with the greatest number of dams is Worchester County, Massachusetts, with 425. These ubiquitous barriers have an impact on river hydrology that is greater than any impact likely to result from global climate change (Graf 1999).

One measure of their effects is their total combined storage capacity, which is equal to nearly one year's mean annual runoff from the entire nation. In the Upper Colorado River Basin and the Rio Grande Basin, dams store more than three years' mean annual runoff. The segmentation of rivers and the partitioning of watersheds by dams produce a national fluvial system that operates in bits and pieces rather than as an integrated system. By some measures, only about 2 percent of the 3.5 million miles of streams in the United States is unaffected by dams, and 18 percent is under the waters of reservoirs. Dams divide watersheds into subregions that range in average size from 43 km^2 (17 mi^2) in New England to 43 km^2 (313 mi^2) in the Lower Colorado Basin.

The demonstrable fact that American rivers function as divided systems has strong implications for science and policy. Fluvial science as practiced by hydrologists and particularly by geomorphologists has emphasized rivers as integrated systems, with water, sediment, energy, and nutrients flowing smoothly from one part of the system to the other. Most of our mathematical and conceptual models of these systems emphasize the transmission of changes throughout the system, from point sources to places downstream. In the real world in which we seek to apply these concepts, dams interrupt and modify the long-distance transmission of system influences, and effects of natural environmental controls such as flood events or of artificial controls such as land use changes are either constrained or changed by dam-related disruptions in the fluvial system. To be useful for river management, scientific advances in geomorphology must emphasize the operation of fragmented systems and cybernetic systems, wherein technology is an integral part of understanding river and watershed behavior.

Segmentation of rivers and fragmentation of their watersheds also have implications for policy makers. The bureaucracy of river management in the United States is itself highly fragmented, with numerous agencies at local, tribal, state, and federal levels having partial responsibility for river management. Agencies often have missions that are commodity-driven rather than watershed- or ecosystem-specific, so that the administrative boundaries of management agencies do not coincide with the physical boundaries of the watersheds that are the physically rational units for decision making. At the federal level alone, twenty separate agencies have at least some responsibility for river management (Table 1; National Research Council 1999, 168), but the internal regional boundaries are different from one agency to another.

One solution to administrative fragmentation is the use of river basin commissions, but they have had a checkered history in the United States. Orchestrated by the National Water Resources Council, river basin commissions and interagency commissions were features of the hydro-bureaucracy from the 1930s until the early 1980s, when the Reagan administration suspended funding for them (Featherstone 1996). Some commissions were largely unsuccessful even with funding, because federal and state agencies were reluctant to delegate their decision making powers to external regional groups (Ingram 1973) and because the political climate of the period of their activities emphasized a top-down, federally driven process. However, the devolution of authority from federal to state entities at the beginning of the twenty-first century, along with increasing recognition of the regional nature of river issues, may imply that the time is right for a revival of the commissions. Several interstate compacts for river management enjoy moderate success, including the Great Lakes Basin Compact, Chesapeake Bay Commission, and the Colorado River Compact. As states assume more authority from the federal government for water resources and rivers, they are increasingly establishing watershed-based organizational structures that include state, tribal, and local components (Figure 4), with notable success. California alone has several hundred environmental and resource management programs organized according to watersheds (McClurg 1997). Such arrangements are either implemented or are in progress in twenty states (Figure 4), though the experience of Florida water-management districts suggests that the issue of sharing of powers is still problematic.

Physical Integrity

Researchers and administrators have paid scant attention to physical integrity, yet the physical structure of rivers provides the substrate for their biological systems and a context for their chemical systems. No river restoration effort, particularly restoration of aquatic or riparian habitat, can succeed without first addressing the restoration of physical integrity as a foundation. A first approximation to a working definition for physical integrity is:

> *Physical integrity* for rivers refers to a set of active fluvial processes and landforms wherein the channel, flood plains, sediments, and overall spatial configuration maintain a dynamic equilibrium, with adjustments not exceeding limits of change defined by societal values. Rivers possess physical integrity when their processes and forms maintain active connections with each other in the present hydrologic regime.

Table 2 provides definitions of the terms.

Central features of the concept of physical integrity include the emphasis on active processes and forms and the recognition of a changing or dynamic equilibrium rather than the establishment of a static and completely predictable state. A river with physical integrity is an active system, functioning to transport, store, and remobilize water, sediment, and nutrients. Changes in fluvial landscapes and riparian habitats occur under entirely natural circumstances, and the changes continue at a reduced magnitude when rivers are subject to technological control. The objective of most river engineering efforts is to produce a stable, unchanging, predictable system. Social and economic values determine how much instability is acceptable in the partially controlled system, usually working to establish a tradeoff between the benefits of flood control, water supply, power generation, and navigation and the costs of losing natural functions of the river.

The Mississippi River provides an example of how social values influence the physical integrity of a river. Under pretechnological conditions, the Middle Mississippi River was a sinuous channel that frequently moved across an active flood plain more than 80 km (50 mi) wide. In 1543, a member of de Soto's expedition reported the lower river to be flowing in a flood 100 km (60 mi) wide (Barry 1997, 173). Massive engineering efforts and the investment of several billion dollars produced a system of flood control dams in the upper basin, along with modified channel alignment and an extensive levee system in the middle and lower basins (e.g., Moore 1972; Clay 1986). Throughout the mid-twentieth century, levees encroached on the river, reduced the active flood-plain area, and converted the channel to a simplified conduit. However, these huge investments did not stem the tide of flood losses. During the massive 1993 floods in the lower Missouri and upper Mississippi rivers, high flood waters breached many levees, returning to some flood

Table 1. Federal Agencies Directly Involved in Water Resource and River Management

Agency	Water Supply	Flood Management	Water Quality	Erosion-Sediment	Restoration-Biodiversity	Flow Regimes	Fisheries	Wildlife	Preservation	Recreation	Navigation	Hydropower	Research	Wetlands	Estuaries
Department of Agriculture															
Farm Services Agency				1	2									2	
Forest Service	2	2	2	2	1		1	1	1	1			2	2	
Nat. Resource Cons. Service		2	2	1	2	2								1	
Agricultural Research Service	2		2	2									1		
Department of Commerce															
National Marine Fisheries Service			2				1	2			2			2	1
Nat. Ocean. & Atmos. Admin.		1	1				1								1
U.S. Army Corps of Engineers	2	1	2	2	2	1					1	1	2	1	
Department of Energy															
Federal Energy Regulatory Comm.												1			
Department of the Interior															
Bureau of Land Management			2	2	1	1		1		2			2	1	
Bureau of Reclamation	1	1	2	2	2		2	2		2		1	2		
Fish and Wildlife Service			2		1		1	1	1	2			2	1	
Geological Survey	1	2	2	2	1	2	2	2					1	1	2
National Park Service			2	2	1		1	1	1	1				2	2
Bureau of Indian Affairs		2	1	2	2		2	2						2	
Department of State															
International Boundary Comm.	1	1	1												
Other Federal Units															
Environmental Protection Agency	2		1	2	1	2	2	2	2	2			1	1	2
Tennessee Valley Authority	1	1	1	1	2	1	2	2		2	1	1	2	2	
Bonneville Power Administration	1	1	1	2	1	2	1	2			1	1		2	
Fed. Emergency Manag. Agency		1													sa
Joint International Commission	2		2	2	2		2				1			2	2

Source: National Research Council (1999, 168).
Note: An entry of 1 indicates significant responsibility; an entry of 2 indicates related responsibilities.

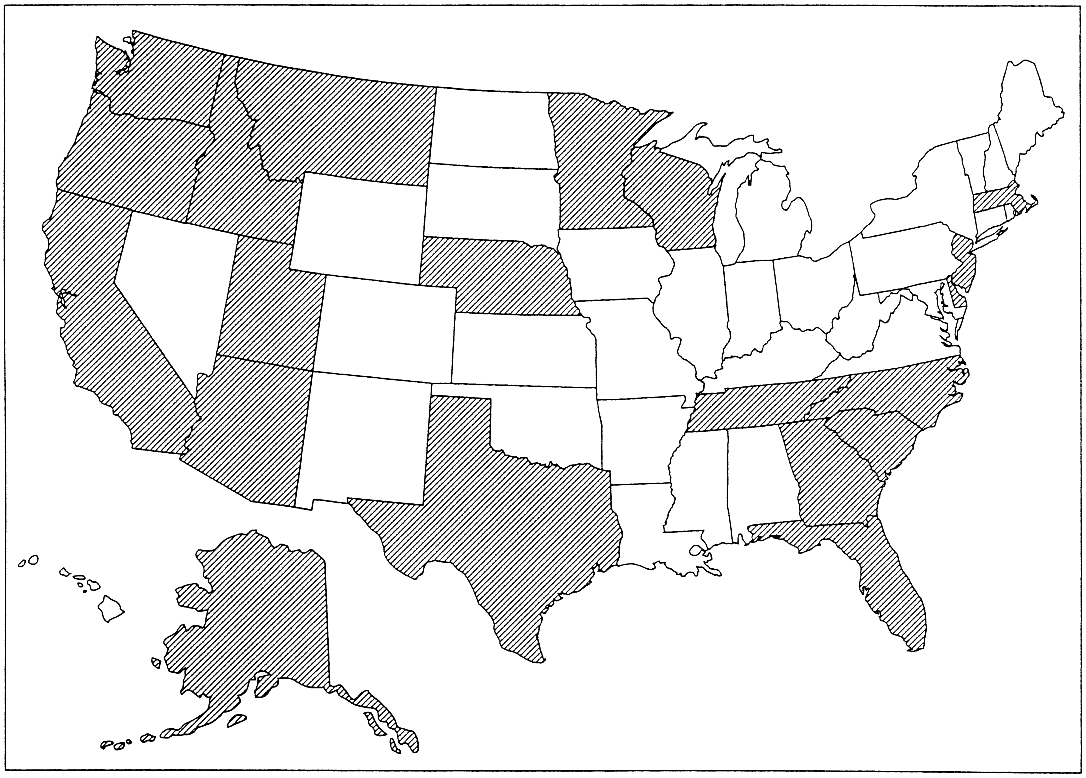

Figure 4. Map showing states (shaded) with water-related resource management structures specifically designed according to watershed boundaries. Data from Nagle et al. (1996).

plains and renewing a national debate about levee construction (Scientific Assessment and Strategy Team 1994). The question of how much flood plain to leave as an active part of the river system and how much to isolate for agriculture and town sites had a direct effect on the physical integrity of the stream, particularly in determining the amount of space available for riparian wetlands along the active channel. The general conclusion was to continue reliance on levees in many areas, but also to examine, where feasible, the return of some flood plains to a more natural state by land acquisition or home relocations. The Mississippi River re-

Table 2. Terms Used in the Definition of Physical Integrity for Rivers

Term	Definition
Streams and rivers	Those parts of the landscape with confined surface flow
Fluvial processes and forms	Processes and forms directly related to the physical operation of the confined surface flow
Channel, near-channel landforms, sediments	Channel is the area of confined flow active in the present regime of the river (active at least once per century); near-channel landforms include surface forms that interact with the confined flow in the present regime of the river, including flood plains; sediments are those deposited in the present regime of the river
Configuration	Planimetric and cross-sectional arrangements of the surfaces of the channel, near-channel landforms, and sediments
Dynamic equilibrium	The tendency for most physical indicator parameters to be changeable with definable mean values over a period of a few years, but with changing means over a period of 100 years
Limits of change defined by societal values	Dimensional and spatial changes in streams and rivers are part of their natural behavior over a period of 100 years, but societal values determine how much change is accepted before structural intervention by dams, levees, or other means restricts change; some streams have socially acceptable unlimited change, as in wilderness rivers
Hydrologic regime	The century-long behavior of water flow as defined by daily measurements of magnitude, frequency, duration, seasonality, and rates of change

mains largely unnatural and lacks many aspects of physical integrity.

Functional Physical Systems

The physical integrity of rivers has a distinct geographical expression in the distribution of fluvial and riparian forms, materials, and vegetation because all these features are spatially related to each other and have specific operational connections with each other in *functional physical systems*. They have coincidental distributions, arrangements, and patterns. For example, in many dryland streams of the Southwest, mesquite bosques (forests) are associated with fine-grained soils and sediments, which in turn are associated with active flood plains (Cleverly and Smith 1995). Mesquite trees rarely grow in the coarse sediments of active channels, in the mixed sediments of channel bars, or on sandy beach deposits on the channel margin. Thus, in many river reaches of the Southwest, to map the mesquite bosque is also to map a particular landform and its soils.

Hydrologic connectivity is a critical aspect of functionality. For example, under pretechnological conditions, the flood plain of the Missouri River had a direct and frequent connection to the bed of the main channel because of annual or biannual floods that over-topped the banks that separated the two surfaces. Native fishes in the Missouri used the flood plain as a habitat and feeding area during these flood events (Hesse 1996). By 1955 the closure of several large dams on the main stem of the Missouri and thousands of dams on tributaries dramatically reduced these frequent floods and deactivated the flood plain by functionally disconnecting 178×10^6 hectares from the main channel. Declining fish stocks in the river resulted, with the ultimate potential loss of as much as 98 percent of the original population (Karr and Schlosser 1978). The associated change in riparian vegetation was also dramatic and is likely to explain declines in riparian bird populations. Between Sioux City and St. Louis, flood plains along the Missouri that in 1880 had 65 percent of their surfaces covered by hardwood forest now bear less than 5 percent forest coverage (U.S. Fish and Wildlife Service 1980).

The key to spatial associations of landforms, sediment, and vegetation is functionality. Many riparian trees require frequent, but not annual, fertilization of newly deposited fine sediments. Such an arrangement is only possible on a true flood plain: a relatively flat surface, next to the channel, separated from the channel by banks, with sediments active in the present regime of the river. The flood plain is therefore much more than simply a form: it is a functional surface, recognizable by its form, materials, and vegetation. It can be mapped easily from

Table 3. Examples of Functional Physical Systems* on the Complex Missouri River and the More Simple Salt and Gila Rivers in a Dryland Area

Functional Surface	Physical Description	Habitat Implications
Missouri River		
Main channel	Main channel, riverbed with water depth greater than 1.5 m	Primary activity area for fish
Main channel border	Main channel, adjacent to river bank	Rapid growth vegetation
Chute	Subsidiary channels with water depth less than 2.0 m	Breeding area for fish
Pool	Scour holes downstream from sandbars	Cool water zone for fish
Tributary confluence	Area where smaller stream enters the main stream	Seed bed for aquatic vegetation
Sandbar	Deposition area with water depth less than 1.5 m	Mid-channel riparian forest zone, bird habitat
Backup	Chutes with upstream end filled, cut off from main channel	Breeding area for fish
Marsh	Abandoned channel areas	Complex wetland ecosystem
Oxbow/puddle	Open water area, abandoned channel no longer connected to river	Complex wetland ecosystem
Terrestrial sandbars	Eolian dunes on flood plains and terraces	Riparian forest zone, bird habitat
Islands	Flood bars left elevated after flood events	Riparian forest zone, bird habitat
Salt and Gila Rivers		
Low flow channel	Thalweg, lowest part of channel, active a few times per year	Primary activity area for fish
High flow channel	Active channel, occupied less frequently than annually	Emergent vegetation, scrub, juvenile trees
Islands	Flood bars left elevated after flood events	Riparian forest zone
Bars	Sand accumulations active once or more annually	Temporary emergent vegetation area
Engineered surfaces	Excavations for sand and gravel mines, built surfaces	Artificial, simplified ecosystems
Terraces	Not active in the present regime of the river	Dense riparian forest, bird habitat

Source: Data on Missouri River from Hesse (1996); data on Salt and Gila Rivers from Graf (1999).
* Also referred to as principal habitat types from a biological perspective.

aerial photography, and if it is identified as a functional surface related to periodic flooding it performs specific physical, biological, and chemical roles in the fluvial system. Most Great Plains and Southwestern desert streams have simple sets of functional surfaces that partition the space associated with them, with each functional surface having a distinct morphology, soil, and vegetation association (Table 3).

The practical consideration of functional physical systems is that they are a useful shared concept between researchers and decision makers. Researchers use the surfaces and associated materials and vegetation to describe the river and interpret its behavior, while the policy maker attaches social values to these features, and decides on land-use strategies for them. In restoration projects, decision makers also may chose to eliminate some functional surfaces, add others, or change their dimensions for the convenience of human users. In the case of the mesquite bosques, which form an important habitat for riparian wildlife, a reasonable social goal might be to expand mesquite coverage. However, because the trees are associated with flood plains, the only strategy likely to see long-term success is one of expanding the necessary physical basis required for mesquite forests by maintaining enlarged, functional flood plains. If this approach is not possible because of the controls on discharges exerted by upstream dams, or because of the need to protect particular property, restoration efforts will have to focus on nurturing vegetation communities other than mesquite.

Physical Indicator Parameters

The mapping and assessment of functional systems provide insight into the landscape and ecosystem consequences of changing river behavior. Ongoing processes and responses to management efforts or to natural changes require measurement and monitoring of *physical indicator parameters*. Long-term monitoring requires a small set of simple, easily defined parameters that are sensitive to changes in the physical system, similar to indicator parameters used for biological and chemical integrity. For biological applications, for example, the frequency of occurrence of a particular species in particular locations is often related to the overall health of an entire riparian ecosystem. Concentrations of particular potentially hazardous chemical compounds in surface or ground waters can be compared with accepted safety limits to measure the chemical integrity of a river. Recent advances permit the assessment of the hydrologic integrity of a river by statistically analyzing flow records (Richter et al. 1996; Richter et al. 1998), but similar assessments for geomorphic components are not yet agreed upon. For the assessment of physical integrity, an endless array of possible parameters are available for measuring and monitoring geomorphic change within a reach of a few km. However, the most useful parameters must be few, quantitative, firmly established in the scientific literature, directly related to the resolution of force, resistance, and work in river processes, easily and cheaply measured by nonspecialists, and applicable to a wide range of channel types and sizes.

In classic fluvial theory, the parameters used to describe basic river processes are channel width, depth, gradient, hydraulic roughness, flow velocity, water discharge, sediment discharge, and sediment size (Leopold, Wolman, and Miller 1964; Leopold 1994). Additional closely related parameters include channel sinuosity and pattern. Depth and flow velocity, though easily measured in small streams, are highly variable and are difficult and expensive to measure in large rivers. Analysts can measure hydraulic roughness, but in usual practice they estimate it, leading to problems of standardization. Sediment discharge measurements are not commonly available for many important streams (U.S. Geological Survey 1998, 12), and the quality of existing measurements is highly suspect. For example, most standard sediment discharge measurements are for fine sediment suspended in the flowing water, completely ignoring the unknown but substantial bedload traveling on the floor of the channel (Garde and Raju 1977, 262).

The utility of physical indicator parameters is in their ability to detect and measure change in fluvial systems. With periodic measurements and the construction of a time series of parameters, either from historical sources or from continuing repetitive assessments, changes in the parameters serve as trip-wire indicators of perturbations and as yardsticks to assess engineering or management affects as well as the impacts of more "natural" forces for adjustment (see Allred and Schmidt 1999, for example). In adaptive management strategies, such changes key a continuous decision making process with adjustments to achieve desired goals. The exact measures of indicator parameters are not inherently "good" or "bad," but changes in them have associated quality judgments derived from societal values.

The measures with the greatest potential to serve as physical indicator parameters and to aid the connection between river science and policy are width, water discharge, sinuosity, pattern, and particle size of bed material. Three of these five indicator parameters—width, sinuosity, and pattern—are spatial characteristics of rivers susceptible to analysis using geographic theory and the technology of geographic information systems. *Width* (measured once every one to five years) is the most obvious single physical measure of a river within a reach, and it is easier to measure than any of the other parameters. Direct measurement is possible for small streams, infrared or laser measurements are accurate for intermediate size rivers, and measurement from aerial photography provides widths for the largest streams. Width has an added advantage as an indicator parameter because of its sensitivity. According to large numbers of measurements made for hydraulic geometry, it is the variable that responds most to changes in discharge (based on classic hydraulic geometry; recently reviewed by Gordon, McMahon, and Finlayson 1992).

Water discharge is the single most important explanatory variable in many geomorphic and hydrologic models for rivers. The U.S. Geological Survey provides historical and real-time daily measurements of water discharge for many American rivers. About 8,000 measurement sites are presently active, but some measurements are available for more than 13,000 sites (Wahl, Thomas, and Hirsch 1995). The exercise of legal rights to water withdrawal from streams has historically required continuous monitoring, and many discharge measurements derive more from rights adjudication of the total annual water yield than from the need for scientific measurement. More recently, the magnitude of the lowest allowable flows required to maintain particular aquatic species or riparian ecosystem has driven some monitoring requirements (Gillilan and Brown 1997). The highest magnitude flows are most important in flood protection efforts, with the 100-year flood being the benchmark for planning and mapping in the national flood plain insurance program administered by the Federal Emergency Management Agency.

From the perspective of physical integrity, the most important discharge is bankfull, which occurs when the channel is completely filled with water but does not spill over onto adjacent flood plains. Bankfull discharges on average occur once every year or two, though there is great geographic variation in their return intervals (Williams 1978). Because bankfull discharge is especially important in forming and maintaining the channel, it is directly connected to physical integrity. Bankfull discharge cannot be the only determining factor in restoration decisions, because it responds to watershed conditions and human controls outside any given reach (Doyle, Boyd, and Skidmore 1999), but it is a central, widely recognized concept in such efforts.

Channel sinuosity and *pattern* represent easily observed and measured parameters that are enshrined in the scientific literature as important indicators of river behavior. These two parameters are also of great interest to river managers because they are highly visible to the public and are subject to engineering "fixes." Sinuosity is the ratio of the along-channel distance to the shortest possible straight-line distance; the ratio ranges from about 1.05 for nearly straight channels to values greater than 2.0 for highly sinuous streams such as the Loup River of Nebraska. Sinuosity is a useful physical indicator parameter because it is directly related to gradient and thus to the velocity of flow, sediment transport capacity, stream power, and shear stress, all factors with implications for channel stability.

Stream channel patterns are also distinctive physical indicator parameters because each pattern is related to a particular hydraulic behavior. Single-thread, meandering channels have flood plains and modest annual variations in flow. Braided channels have multiple threads, may lack flood plains, and experience large annual flow variations. Compound channels are hybrid patterns, with a single meandering thread for low flows set within a larger braided channel for high flows, a pattern common downstream from dams that occasionally spill. Pattern is a useful integrative parameter because it is an expression of hydraulic behavior responsive to climatic or human influences. Switches from one pattern to another result from changes in discharge regimes or sediment supply and are indicators of widespread environmental adjustments that are likely to extend far beyond the river. Although managers may attach value judgments to these patterns—with a single-thread, meandering channel thought to be the most desirable (U.S. Bureau of Land Management 1998)—any pattern may occur in rivers with physical integrity, depending on water, sediment, and vegetation.

The *particle size* of material on the channel bed is an important indicator of river processes. Particle size is sensitive to the nature of materials supplied to the channel from the upstream watershed as well as to the river's ability to transport the material. Periodic measurements of particle sizes can reveal changes in sediments released into the river from natural erosion or accelerated erosion caused by human activities or through intentional dumping. Sometimes sediment size reflects starvation from upstream traps, usually of the finer materials, so that there is a progressive coarsening of bed sediments.

The Predominant Role of Change

Much of classic river science emphasizes a tendency toward equilibrium, and most public policy for rivers seeks to establish an unchanging and therefore predictable system. In contrast, research throughout the past two decades has emphasized how and why rivers *change*, and has shown that *change* is the hallmark of fluvial geomorphic systems and riparian ecosystems. Changing hydrologic conditions dominate annual cycles of discharge on most American rivers, so that the systems accommodate yearly maximum flows that are two to three times the annual mean for streams in the eastern United States. In many western streams the annual maximum flows are more than thirty times the annual mean. Year to year fluctuations are even more dramatic, so that the mean annual flow in eastern streams varies by several hundred percent and in some western streams by two orders of magnitude. In natural streams these radical changes in discharge, the primary driving force in fluvial systems, produce physical features specifically attuned to the changes. Flood plains act as overflow zones for flows that exceed channel capacity in humid regions, while in dryland settings channels adopt braided arrangements or have a compound geometry. Riparian vegetation communities adapted to annual and interannual changes require changing hydrologic inputs for their continued health.

The imposition of dams and other technological controls on the natural hydrology of rivers upsets this change-based arrangement by reducing the annual and interannual range of flows. For example, annual peak flows on the uncontrolled Colorado River were probably similar to other southwestern rivers, many times the annual mean flow. The fluvial landforms and riparian vegetation communities along the lower Colorado River adapted to these conditions. During the twentieth century, however, the construction of numerous large dams in association with the Colorado River Storage Project changed the flow of the lower river, so that now at the U.S. Geological Survey measurement site near Yuma, Arizona, the annual peak flow of the river is only 2.6 times the mean (Graf, Stromberg, and Valentine forthcoming). The result of these altered flows, along with levee construction and wetland drainage, has been a radical simplification of the geomorphology of the river and the loss of much of its original diverse habitat and many associated bird and fish species.

The implications for policy of the recent research showing the importance of change in rivers is that planning and management for them must take change into account rather than trying to completely suppress it. While it is unlikely that as a society we would wish to return all rivers to their original natural conditions and forgo the economic and social benefit we derive from dams and their associated technology, it is possible to envision management systems for rivers that provide some space for channel and habitat changes. Because channels and riparian communities downstream from dams are typically smaller than their natural predecessors, change may also be less and still maintain some physical integrity. In other words, if the magnitude of mean flows is now half the former magnitude, it is reasonable to arrange dam releases with standard deviations that are also half the former ones (Bravard 1998). French researchers recently advocated planning and management that allows "living space" for rivers by increasing the width across rivers between levees, a strategy that could be linked to modified dam operating rules to permit the use of excess water for mimicking natural flows, albeit at reduced scales.

What is Natural?

Assuming that river researchers and policy makers use functional physical systems and physical indicator parameters to determine the degree of physical integrity for a given reach of river, and assuming that social values dictate restoration efforts to accommodate change as well as to mitigate the impacts of dams, levees, and other engineered structures, a significant philosophical question remains. Many restoration efforts specify as an objective the return of river to its natural condition, but what is "*natural*"? To what arrangement should the river be restored: a primeval condition that existed before the advent of humans (as defined by National Research Council 1992), a pretechnological condition that included some human influence, or some condition exhibiting partly natural and partly technological influences? What do citizens consider to be natural, particularly given that most recognize the desirability of more natural conditions but also know the necessity of designed controls?

Given the pervasive influence of dams and human land use throughout the nation, almost any river reach of interest is likely to be subject to at least some human influences. With few exceptions, a restoration goal of anything other than a mixture of artificial and natural influences is not possible (Schmidt et al. 1998). Rather than deal with absolutes of "natural" and "artificial," researchers and policy makers should view American rivers as hybrid features with varying amounts of human influence on their forms and processes. Each river reach exists on a scale of naturalness ranging from nearly natural to completely artificial (Graf 1996). There has already been considerable progress in experimental naturalization of river discharges using dam operations to mimic partially natural flows (Haeuber and Michener 1998). Examples include the Mississippi and Missouri systems (Galat, Robinson, and Hesse 1998; Sparks, Nelson, and Yin 1998), Rio Grande (Molles et al. 1998), Colorado River (Schmidt et al. 1998), Kissimmee River (Toth et al. 1998), Gunnison (Chase 1992), and Trinity River (Kondolf and Wolman 1993).

For physical integrity, the primary consideration for naturalness is diversity of geomorphology and hydrology. On a scale of geomorphological naturalness applicable to

Table 4. Scale of Naturalness for the Geomorphology of River Channels

Components of Channel Physical Integrity	Geomorphological Naturalness: Completely Natural	Partly Modified	Substantially Modified	Mostly Modified	Completely Artificial
Channel pattern	Pretechnological pattern, often meandering single thread or complex braided	Minor portions of the pattern altered by engineering works	About half of the channel pattern is engineered	Only remnants of pretechnological pattern remain	Completely engineered channel pattern, usually straightened and single thread
Channel cross-section	Pretechnological cross-section, often highly complex	Minor portions of the cross-section altered by human activities	About half of the cross-section is altered by human actions	Only remnants of the pretechnological cross-section remain	Designed, completely engineered cross-section, usually highly simplified
Minor landforms (bars, islands, pools, riffles), functional surfaces and materials	Pretechnological sizes and distribution of minor landforms, often highly complex	Minor changes in size or distribution of minor landforms as a result of human activities	About half of the minor landforms of the reach altered by human activities	Only remnants of the pretechnological minor landforms remain	Minor landforms in the channel eliminated by engineering, or artificial forms included by design
Descriptive notes	River undisturbed by technological activities, could be a "wild" river under the Wild and Scenic Rivers Act	River retaining much of its pretechnological characteristics, but with some modifications and/or impacts, often from altered flows of water or sediment	Combined "natural" and artificial river, with obvious intentional modifications and/or unintended human impacts	River with major, extensive modifications and/or impacts	River as a product of design and engineering
Example	Middle Fork of the Salmon River, Idaho	Lower St. Croix River, Wisconsin and Minnesota	Concord River, Massachusetts	Lower Colorado River, Arizona and California	Los Angeles River in downtown Los Angeles, California

Source: Simplified and modified from Graf (1996).

a river reach a few km in length, the extremes of completely natural and completely artificial are easily defined, if not often observed, while the gradations between the extremes are largely a matter of arbitrary definition (Table 4). The major determinants of geomorphological naturalness are channel pattern, cross-sectional shape, minor channel landforms such as islands and bars, and the percentage of channel area that is engineered. A similar scale for hydrologic naturalness also ranges from completely natural to completely artificial, with intervening gradations determined by short-term fluctuations in flow, human induced changes in short-term fluctuations, magnitudes of annual mean high, mean, or low flows, annual water (and thus energy) yield, and the timing of peak or low flows (Table 5). Many human activities introduce artificial components to a river's hydrology, including such land use practices as agriculture, lumbering, mining, and urbanization, but the most important influence is that of dams and their operating rules. Detailed methods of assessing the impacts of dams on downstream flows depend on statistical measures of daily or hourly discharge measurements (Richter et al. 1996).

Application of a naturalness scale for geomorphology on the Salt and Gila rivers of Arizona exemplifies the policy- and decision-making applications. Sponsored by the U.S. Army Corps of Engineers, Graf, Beyer, and Wasklewicz (1994) evaluated 65 km (40 mi) of the Salt and Gila rivers in the urbanizing Phoenix area in a search for reaches likely to host successful environmental restoration projects. The Corps sought to identify reaches where federal and local investment was likely to create physical and biological conditions more useful for than present conditions for native plant, bird, and animal species. In this urbanizing area, 45 percent of the river length was completely artificial or mostly modified (as defined in Table 4), representing portions of the river that are urban sacrifice zones given over to channelization works or sand and gravel mining. On the other hand, although none of the river length was completely natural, 24 percent of it was essentially natural or only partially modified. In subsequent proposals to local governments and Congress, the Corps recommended no investment for restoration purposes in the completely artificial or mostly modified reaches, and only sparse investment in those reaches that had conditions in the middle of the scale of geomorphic naturalness. The Corps recommended investments for restoration in those reaches that had conditions that were partly modified, because it was most likely that restoration efforts would be successful there. In essence, the changes needed to move the partly modified reaches toward the natural end of the scale were smaller than in other cases.

Table 5. Aspects of Naturalness for the Hydrology of River Channels

River Flow Characteristics	Common Effect of Dams ➥	Social and Economic Benefits ➥	Impact on Physical Integrity ➥	Habitat Consequences ➥	Compromise Adjustments
Magnitude, frequency, and duration of low flows	Increase	Improved delivery of water to downstream users, improved navigation	Establishment of a simplified low flow channel	Reduced landscape complexity, loss of fine grained soils	None
Magnitude, frequency, and duration of high flows	Decrease	Flood reduction	Channel shrinkage, reduced sediment and nutrient transport, deactivation of flood plains, simplification of system	Reduced landscape complexity, shrinkage of riparian habitat	Release of controlled floods, abandonment of hazardous areas to allow less flood control
Range of flow magnitudes	Decrease	Improved planning capability and predictability	Deactivation of much of the channel cross section	Shrinkage of entire ecosystem, reduced complexity	Release of controlled floods in periods of excess water
Timing of high flows	Shifted from natural spring peaks	Improved timing of delivery for downstream users	Increased erosion if high flows occur in months without extensive vegetation	Disruption of seed dispersal and germination that require spring floods	Release excess water to create highest flows similar to timing of uncontrolled floods
Ramping rates*	Increased	Improved control of hydroelectric power production	Increased erosion of banks, islands, and bars	Destabilization and loss of seed beds	Reduce rates of change for water releases

* Rate of change between flows of different magnitudes.

Naturalizing rivers to some compromise condition is increasingly common at a variety of decision making scales. In Grand Canyon National Park, restoration of the Colorado River depends on operating rules for Glen Canyon Dam, immediately upstream from the park. Operating the dam to create moderate artificial "floods" partially mimics the predam river conditions to create aquatic and riparian habitats more natural than otherwise would be possible, but the purely natural conditions of a century ago are unattainable (Carothers and Brown 1991, 188). Management of the river therefore emphasizes maintenance of a partly natural, partly artificial system.

For smaller streams, the channel may be largely a product of human activities, so that restoration is actually the creation of something entirely new that has a more natural appearance. For example, small streams on the formerly wet prairies of northern Illinois are large ditches created by farmers to drain the relatively flat-lying till and outwash plains for agriculture. Rhoads et al. (1999) showed that by working with local farmers it was possible to naturalize some ditch/streams to more river-like forms and processes. The resulting more diverse aquatic habitats enrich the otherwise mostly artificial regional ecosystem.

The scientific and technical challenge of naturalization is to determine what is possible in any given river reach and then to design efforts to achieve a goal that is scientifically sound as well as consistent with local social values. The connection between science and socially defined goals is exceptionally important to avoid unreasonable expectations, because culturally defined objectives may be incompatible with environmental reality. For example, planners and managers in many western states seek to restore streams to fully functional biological conditions as directed by Congress (U.S. Bureau of Land Management, 1998). In this process managers seek to create in small and medium scale streams narrow, meandering, single-thread channels with heavily vegetated flood plains, because they believe such arrangements are likely to foster highly productive, diverse biological systems. However, in many steep gradient or dryland settings that are common in the West, braided or compound channels are frequently the only forms likely to be stable on a long-term (multidecadal) basis. Given the social or cultural biases of managers and the public, often derived from humid-region stereotypes, these likely alternatives to meandering single-thread channels receive little attention. Thus, the most "natural" condition may be one that managers and the public consider undesirable.

Misuse of the concept of naturalness leads to policy objectives for large streams that are impossible to achieve. An important example of this problem is the restoration of the lower Elwha River on the Olympic Peninsula in the state of Washington, where two hydroelectric dams are becoming the first relatively large dams to be dismantled to improve environmental quality and repair the physical integrity of a river (U.S. House of Representatives 1992). The dams have impeded the upstream migration of salmon, anadromous fishes that once used the river for spawning and that were an important component of the culture of the local K'lallam tribe. The installation of the dams in 1912 and 1927 prevented the fish from reaching their upstream spawning areas and reduced the annual salmon run from 380,000 fish to less than 3,000 (U.S. National Park Service 1995). The Department of Interior interprets legislation authorizing funds to remove the structures (the 1992 Elwha Act, PL 102-495, section 4a) as directing managers to "fully restore" the physical and biological systems of the river (U.S. National Park Service 1995, i). However, physical conditions on the river makes the achievement of this ideal unlikely because of the 13.5×10^6 m^3 (11,000 ft^3) of fine sediments stored in the reservoirs behind the dams. Removal of the structures will result in the remobilization of the some of the sediments, flushing them downstream to pollute gravel beds. The sediments that remain in place will produce artificial forms and materials and create unnatural habitats. It is unlikely that any reasonable expenditure of money will be able to restore completely natural conditions to the system, despite the fact that management agencies will be legally bound to do so (Pohl 1999).

Some river "restoration" projects use rivers altered by dams or other technology to create new conditions that are completely artificial. One of the oldest American examples, the San Antonio Riverside Walk, is a New-Deal-era project that introduced a complex set of control gates to control the flow of small streams through downtown San Antonio. The completely artificial channel and banks of the system are parts of a built landscape with sidewalks, shops, and restaurants that is more like the landscape of an inner London canal than of a west Texas river. A more recent example of "restoration" to an artificial condition is the Ocoee River of southern Tennessee. Four dams of the Tennessee Valley Authority (TVA) control the flow of the river's downstream reaches. One channel reach is biologically nearly sterile because an upstream dam diverts all the normal flow of the river into a penstock for hydroelectric power generation, and a copper smelter in the watershed has polluted river sediments with heavy metals. In 1992, the state of Tennessee, TVA, the U.S. Forest Service, and a private architectural firm built the Ocoee Whitewater Center in the reach by completely rebuilding the channel to create a world-class Olympic kayak course. The 500 m (1,700 ft)-long rebuilt channel includes a channel only half the width of the original natural channel, with artificial rapids and pools, and water flows supplied occasionally by opening the gates of the dam upstream. The river reach is hardly natural, but it serves a purpose that society values more highly than the previous completely dysfunctional state.

The Probabilistic River

The propensity of rivers to change their locations and arrangements requires researchers and decision makers to adopt *probabilistic methods*. Much of hydraulic research and design policy for rivers adopt a deterministic and mechanical perspective (Dingman 1984; Petts and Calow 1996). In this approach, given a certain range of hydrologic inputs, we assume the river will behave in a predictable fashion. Standard hydraulic equations are derived either from the first principles of physics or from empirical relationships expressed as regression-like equations. However, the geographic aspects of rivers—such as the locations of erosion, sedimentation, or channel migration—that are most important to policy makers are not susceptible to deterministic predictions for at least two reasons. First, our deterministic models of river processes are incomplete—there are more variables than known relationships (Leopold, Wolman, and Miller 1964)—so that even if we had the luxury of perfect measurements we would be unable to construct an elegant mathematical model. Second, it is likely that fluvial systems have built-in random components as products of complex hydroclimatic and human influences.

In lieu of deterministic approaches often based on untested assumptions, historical information about the spatial characteristics of fluvial systems give us insight into probable patterns of behavior (Baker [1994] makes a similar point regarding flood frequency analysis). For example, though the width of a particular river reach might possibly be anything within a fairly substantial range of values, some widths are much more likely than others. Fluvial theory can indicate the most likely values for the dimensions of width and depth of channels (Langbein and Leopold 1964). Historical data can define other spatial aspects of the river reach, such as the most likely locations for bars, islands, and meanders. Each location in the fluvial and riparian system has some probability of being the site of part of the low flow channel, another probability of being the site of an island, or flood plain, or other feature. A locational probability map (Figure 5)

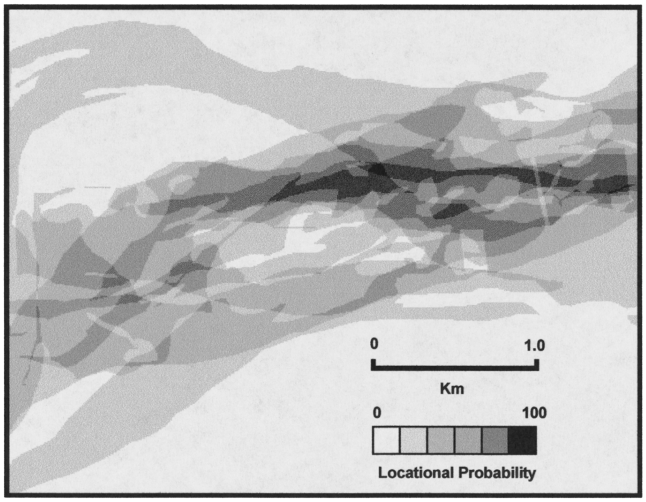

Figure 5. Map showing the locational probability for the low flow channel of the Salt River in a reach of the stream near Phoenix, AZ, based on analysis of historical aerial photography. The darkest portions of the map have the highest probability of being the location of the low flow channel. Figure modified from Graf (2000).

based on observations of past conditions provides a statistical view of the geography of the river that reflects its most likely arrangements (Graf 1984a). Restoration and other management policies can use this view as an input for locational decisions. For example, decision makers considering where to locate restored wetlands might seek to avoid areas of high channel mobility, so that a locational probability map of the river becomes a guide to positioning restoration projects (Hersperger 1994).

The most difficult parts of employing probabilistic approaches to rivers are in policy and management, where decision makers frequently do not have a probabilistic worldview. Probability is not a subject that enjoys widespread public appreciation, and decision makers abhor uncertainty even more than do researchers. Nonetheless, researchers are obligated to report to consumers of their work the most probable physical outcomes of policy decisions, along with the degree of risk and uncertainty associated with their predictions (Pielke et al. 1999). The prediction of exact outcomes without associated error envelopes is an invitation to failure and loss of trust between scientist and decision maker.

Watershed and Ecosystem Perspectives

Combined *watershed and ecosystem perspectives* provide a spatial framework for the application of the concepts associated with physical integrity. The introduction by Tansley (1935, 206) of the term ecosystem into the scientific literature in the 1930s and its subsequent broad adoption in environmental legislation, planning, and management during the late twentieth century have meant a critical intellectual advance for American environmental perspectives. Ecosystem concepts emphasize a synthetic approach to environmental science and management by assessing an entire functioning collection of organisms and the inorganic components upon which they rely for survival. By emphasizing the synthesis of many components and their interactions with each other, science and policy can focus on system-wide implications of processes and changes rather than focusing too narrowly on individual, isolated elements of the broader system.

The Greater Yellowstone Ecosystem is a successful example of the application of ecosystem principles that is also appreciated by the general public. This ecosystem encompasses the Yellowstone Plateau and surrounding areas, a unique geologic terrain that supports an amazing variety of natural plant and animal species substantially affected by human management (even though extensive areas of the system are wilderness). By using ecosystem boundaries to define study areas, rather than political boundaries such as the perimeter of Yellowstone National Park, biologists, botanists, and biogeographers deal with a functional system in sorting out causes and effects in environmental change. Planners using ecosystems for "problem-sheds" instead of state and county boundaries devise more integrative solutions to environmental management than would be the case if they worked with competing political jurisdictions.

Ecosystem management has become a common axiom in federal agencies, but the concept has numerous weaknesses in the policy arena (Fitzsimmons 1996). From the standpoint of the physical integrity of rivers, there are two inadvertent shortcomings in the application of ecosystem principles. First, researchers and administrators overwhelmingly emphasize the nonhuman biological components of ecosystems. This emphasis is to be expected because environmental life scientists have accomplished most of the intellectual development of ecosystem concepts. However, the result has been the relegation of the physical substrate to an afterthought in many research designs, and the varied roles of humans are at least under-presented and at most disregarded altogether. The physical components of ecosystems require much more research attention than they have had thus far, because they are the substrate for the organisms, and explanation of changes in environmental life systems are often the products of changes in the underlying hydrologic or geologic systems. From a management perspective, inclusion of the physical components is critical, especially for restoration efforts, because it is impossible to re-establish pretechnology biological systems without suitable landforms, geologic materials, and hydrologic processes.

The second inadvertent shortcoming of the use of ecosystem principles is a lack of a specific spatial framework. Researchers and managers often define the geographic extent of a particular ecosystem by the range of one or more indicator species, plants or animals that are of particular interest. This approach ignores the importance of the underlying physical systems in influencing biotic distributions, and therefore misses the advantage of dealing with primary factors that determine the geographic distribution of the life forms. At the global scale, ecosystems have specific geographies that reflect the dominant influence of climate, while at the continental scale ecosystem geography results primarily from geology and large-scale geomorphology (Brown, Lowe, and Pase 1980). An example of this physically based approach to defining the spatial extent of ecosystems is the newly proposed Greater Grand Canyon Ecosystem. Designed to capitalize on the publicity successes of the Greater Yellowstone Ecosystem, the proposed Grand Canyon example defines the boundaries of the ecosystem according to the earth surface areas dominated by the geologic materials of the southern Colorado Plateau. The result is a functional ecosystem with boundaries determined by particular rock types, soil conditions, and hydrologic processes.

From the perspective of the physical integrity of rivers, the most useful geographic units are ecosystems defined by watersheds. Watersheds provide researchers and managers dealing with rivers with obvious boundaries in most instances, because the entire surface of the earth separates itself into a nested spatial hierarchy of units defined by surface drainage areas. A watershed of any size is a functional ecosystem; more importantly, it is an ecosystem with physically specified boundaries that in most parts of the world are obvious and generally known to the public. Watershed boundaries in the United States are also standardized by the federal government in a three-part hierarchical geographic scheme that divides the nation into twenty-two water resource regions (defined by watersheds), 222 subregions, and 2,150 hydrologic units (Seaber, Kapinos, and Knapp 1987). GIS products specifying the boundaries are available in digital and paper form, providing easily applied base maps for research and management. This set of hydrologic units provides a common geographic framework widely accepted by federal agencies, state, tribal, and local authorities in planning and management. Researchers have been surprisingly slow to take advantage of the system, yet it provides a convenient connection between science and policy for rivers.

Geographic Representativeness

National programs of research that inform us about the physical integrity of rivers and national policies designed to promote preservation and restoration of integrity are most likely to be successful if they are *geographically representative* of the diverse conditions found throughout the country. A geographically representative program includes components from as many regions as possible. Regions for assessing geographic diversity might be defined by geomorphology, hydrology, ecosystems, or socially specified areas such as political jurisdictions. For rivers, biodiversity depends on the underpinnings of geodiversity and hydrodiversity, so research and policies that promote preservation and restoration systems need components from all geographic regions of the nation.

Scientific research into physical processes of rivers is not geographically representative and exhibits regional bias. Prior to 1980, geomorphological investigations emphasized the Rocky Mountains, northeastern glaciated terrain, and California (Figure 6A; Graf 1984b). The distribution of researchers themselves strongly influenced the distribution knowledge (Costa and Graf 1984). The scientific literature disproportionately represented streams close to regional offices of the U.S. Geological Survey or to certain major research universities. Significant geographic gaps included the Great Plains, Appalachia, and the southeastern United States. As a result, available knowledge and theories about physical processes in rivers contained inherent geographic biases. Since 1980, the biases have changed somewhat, but we still have only a distorted geographic view of physical science for rivers (Figure 6B; F. A. Fonstad, conversation with author, 8 November 2000).

Policy for river preservation and restoration is also geographically incomplete. The most prominent recent national policy initiatives for preservation and restoration of rivers, the Wild and Scenic Rivers Act of 1968 and the American Heritage Rivers Initiative of 1996, seek geographic representativeness but fail to achieve it. The Wild and Scenic Rivers Act (PL 90-542) established a national system of river segments to be designated as wild (virtually in their natural condition), scenic (with some evident human impacts), and recreational (with substantial human affects). The purpose of the act is to keep selected river segments free-flowing by prohibiting the construction of dams in the designated segments (Coyle 1988). The Act specifies "free-flowing" but not "naturally flowing," so upstream structures are permissible. Although the original legislation did not stipulate that the system should be geographically representative across the entire nation, executive agencies of the federal government, particularly the Forest Service and Park Ser-

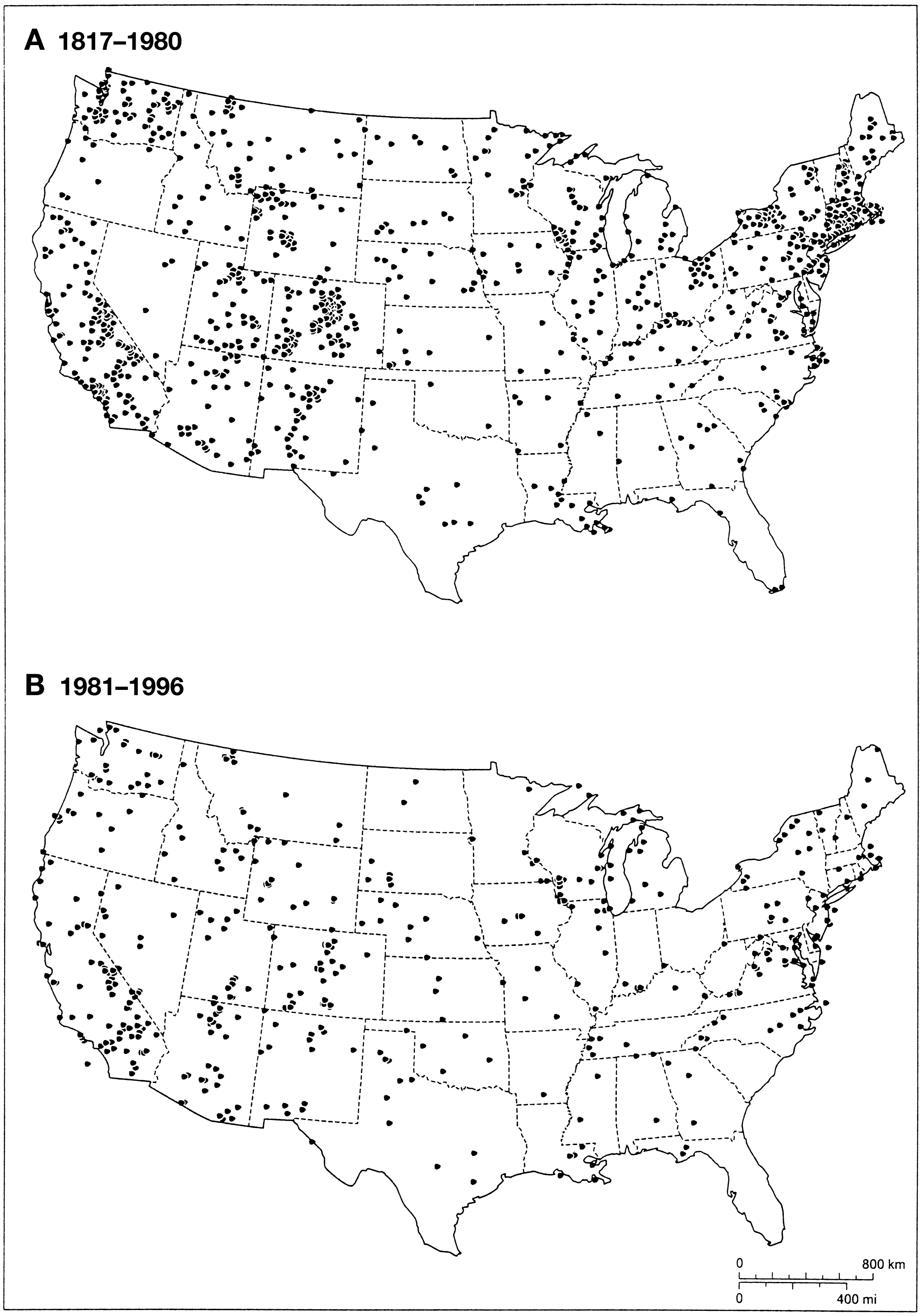

Figure 6. Maps showing locations of field sites for geomorphologic research in the United States published in major scientific journals. A: Research prior to 1980, with major gaps in the Great Plains and southeastern areas (data from Graf 1984b). B: Research between 1980 and 1997 (data from M. A. Fonstad). Both maps designed by M. A. Fonstad.

Table 6. Estimated Length of American Rivers

Physical Condition	Length (km)	Length (mi)	Percent of Total
Affected by human activities	4,022,400	2,514,000	78.9
Drowned by reservoirs[1]	960,000	600,000	18.8
Unaffected by human activities[2]	40,000	64,000	2.0
In the Wild and Scenic Rivers System[3]	17,304	10,815	0.3
Total[4]	5,120,000	3,200,000	100.0

Sources: [1] Echeverria, Barrow, and Roos-Collins (1989), [2] U.S. Department of Interior (1982), [3] Interagency Wild and Scenic Rivers Coordinating Committee (1998), [4] Leopold, Wolman, and Miller (1964).

vice, adopted geographic representativeness as a goal in implementing the act (U.S. Park Service 1982; U.S. Forest Service 1987).

At present, the Wild and Scenic River System includes 17,300 km (10,815 mi) of rivers, but this total is a tiny fraction of the more than 5.6×10^6 km (3.5×10^6 mi) of rivers in the nation (Table 6; Interagency Wild and Scenic Rivers Coordinating Council, 1997). Even this small amount is not geographically representative of the nation's rivers (Table 7). For example, the Colorado River Basin accounts for 7 percent of the nation's area, but only 0.4 percent of river length preserved in the Wild

Table 7. Percent of Wild and Scenic Rivers in Various Geographic Regions of the United States Showing an Unbalanced Presentation of River Basins, Geomorphic Provinces, and Ecosystem Regions

River Basins, Water Resource Regions % of Rivers (% of total U.S. area)		Geomorphic Provinces % of Rivers (% of total U.S. area)		Ecosystem Regions % of Rivers (% of total U.S. area)	
New England	1.0 (2)	Superior Upland	5.6 (1.7)	Western Needleleaf Forests	30.2 (12.6)
Mid-Atlantic and Gulf	2.3 (3)	Coastal Plains, Piedmont	1.7 (13.4)	Western Broadleaf Forests	0.0 (0.6)
South Atlantic	8.0 (7)	Blue Ridge, Valley and Ridge, Appalachian Plateau	4.2 (5.0)	Western Mixed Forests	4.8 (1.7)
Great Lakes	6.2 (3)	St. Lawrence Valley, New England, Adirondack Mountains	1.0 (3.0)	Western Shrublands	2.0 (7.6)
Ohio	2.6 (4)	Interior Low Plateau and Central Lowland	4.6 (11.7)	Western Grasslands	1.8 (4.2)
Tennessee	0.5 (1)	Great Plains	2.8 (20.0)	Western Mixed Shrub and Grasslands	8.4 (8.4)
Upper Mississippi	2.4 (6)	Ozark Plateaus and Ouachita Mountains	2.4 (1.0)	Central and Eastern Mixed Grassland and Forests	2.4 (10.9)
Lower Mississippi	0.3 (3)	Columbia Plateau	11.0 (2.5)	Eastern Needleleaf Forests	3.1 (2.5)
Souris-Red-Rainy	0.0 (2)	Colorado Plateau	0.2 (3.6)	Eastern Broadleaf Forests	6.3 (11.7)
Missouri	4.2 (13)	Basin and Range	3.6 (10.1)	Desert (generally no vegetation)	0.0 (1.0)
Arkansas-White-Red	2.3 (7)	Cascade-Sierra, Pacific Border, and Lower California	23.8 (5.9)	Alaskan Shrub, Needleleaf and Mixed Forests	27.8 (8.8)
Texas-Gulf	0.0 (5)	Pacific Mountains of Alaska	4.0 (5.3)	Alaskan Grassland (mostly tundra)	2.0 (0.8)
Rio Grande	2.9 (3)	Interior and Western Alaska	15.4 (7.4)	Hawai'i	0.0 (1.0)
Upper Colorado	0.0 (3)	Brooks Range	10.4 (1.6)		
Lower Colorado	0.4 (4)	Arctic Slope	0.8 (1.7)		
Great Basin	0.0 (4)	Hawai'i	0.0 (<1.0)		
Pacific Northwest	24.6 (9)				
California	18.5 (4)				
Alaska	30.5 (16)				
Hawai'i	0.0 (<1)				

Sources: Measurements by P.J. Beyer, reported in Graf and Beyer (1993). River basins or water resource regions defined by Seaber, Kapinos, and Knapp (1987), geomorphic provinces from U.S. Geological Survey (1930; from Fenneman 1928), and ecosystem regions by Kuchler (1964).
Note: First number represents the percent of all Wild and Scenic Rivers in the given region; number in parentheses indicates the percent of the total United States land area in the given region. Totals do not add to 100% due to rounding errors.

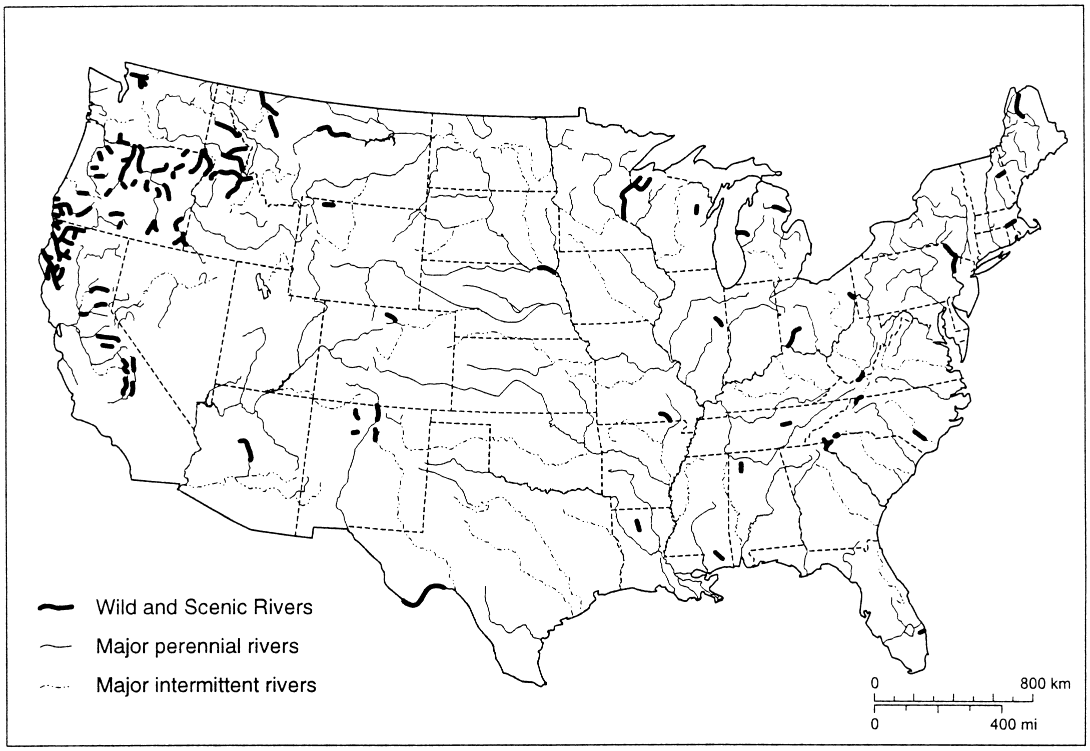

Figure 7. Map showing the distribution of Wild and Scenic Rivers in the United States, with unequal representation across the nation. Data from Interagency Wild and Scenic Rivers Coordinating Council (1997).

and Scenic Rivers System, while the Pacific Northwest, with only 9 percent of the land area, has 25 percent of the preserved rivers (Graf and Beyer 1993). The most remarkably underrepresented regions include the Missouri River Basin, Great Plains, and Coastal Plains/Piedmont geomorphic regions, terrain typified by plains with hills, the central/eastern grassland ecosystem, and the South Atlantic human census region. While regional hydroclimatic differences account for some of the variation, with some regions having more rivers of any kind than other regions, the present Wild and Scenic Rivers System is still geographically unbalanced (Figure 7).

The second primary federal designation for river restoration is the Heritage Rivers system. In his 1997 State of the Union Address, President Clinton announced the American Heritage Rivers Initiative to promote environmental, economic, historical, and cultural restoration of rivers and their adjacent communities. Unlike the Wild and Scenic Rivers Act, which was a product of congressional action, the Heritage Rivers Initiative was a product of the Executive Branch in the form of an Executive Order (Executive Order No. 13061; U.S. Environmental Protection Agency 1997). The President requested proposals from local organizations and consortia for river segments that might be designated as part of the system, with a presidential commission to make the initial selections. Designated river segments and their communities would receive priority funding, streamlined regulatory treatment, and direct federal administrative help in organizing and completing restoration projects. The initiative explicitly called for geographic representativeness in the final collection of heritage rivers, with each major region of the country included in the system (Downs 1999). In the first year of the initiative, local organizations proposed 126 rivers and their communities, a number that exceeded administration expectations by an order of magnitude and that was geographically representative (Figure 8A). The President directed the presidential commission to select ten rivers, and he added four more to the final designated list. However, opposition from a number of congressional representatives led the administration to remove from consideration any river that was in the district of a congressional member who formally objected to the designation. As a result, when the commission completed its work, the initial system was not geographically representative, with the map of American Heritage Rivers reflecting the congressional political map rather than either the distribution of eligible rivers or the active local restoration groups (Figure 8B). Further additions to the system await presidential political developments.

Rivers do not fit well into major federal efforts seeking

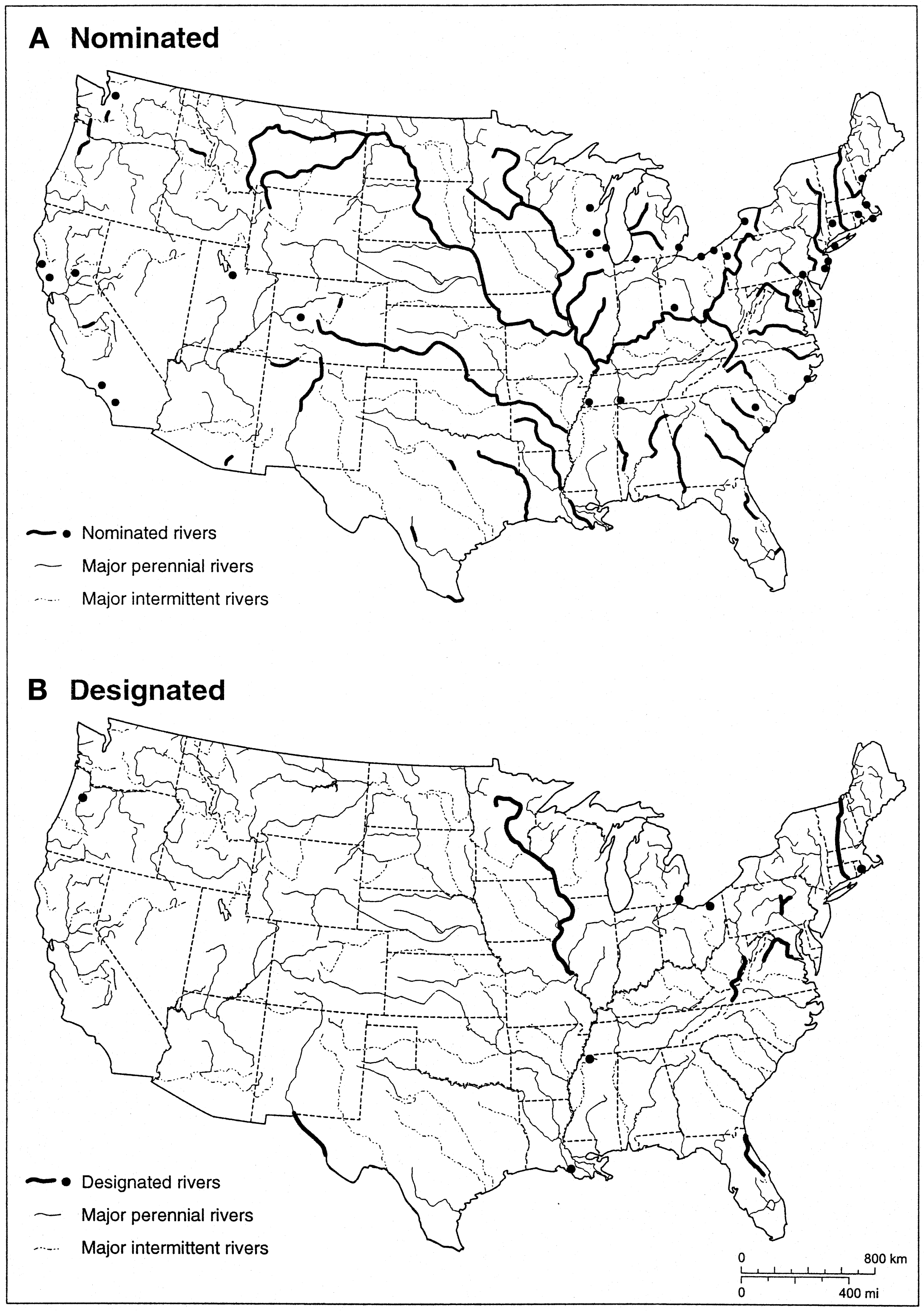

Figure 8. Maps showing the distributions of river segments involved in the initial decision-making processes for the American Heritage Rivers Initiative. A: Rivers nominated by local agencies and organizations showing wide geographic representation. B: Rivers ultimately designed by the initiative, showing unequal geographic representation because of political opposition to the initiative. Data by Graf, from participation in the President's Commission on American Heritage Rivers.

geographic and ecological representativeness in general reserved lands programs. The Biological Resources Division of the U.S. Geological Survey has a Gap Analysis Program, which compares biogeographic regions, species of plants and animals, and land ownership to identify priorities for management and land acquisition (Scott et al. 1993). However, the program utilizes regions of the surface defined by vegetation and mapped from satellite imagery, and thus lacks a framework suitable for river-related policy focusing primarily on corridors. In sum, geographic representativeness in river science and policy is not yet a reality in the United States.

Discussion

At present, the most important public concerns that drive research and policy agendas for American rivers are restoration, endangered species, and the management of dams. Public interest in restoring rivers emphasize habitat and historic reconstruction (especially wetlands), improved flood reduction, and channel stability. Physical integrity of these naturalized systems is an integral part of their success, because functionality with geo- and hydrodiversity leads to the overall stability we seek. Engineering rivers with physical integrity is cost-effective from a maintenance perspective, because this accommodates change rather than attempting to suppress it completely.

The Endangered Species Act of 1973 (PL 93-205; 16 U.S.C.A. §§ 1531–1544) establishes as national policy the preservation of animal and plant species that are in danger of extinction. In practical terms, the law specifies that this end be accomplished through conservation of the habitats upon which the species depend, so the act directly affects management of geographic space. About 30 percent of all threatened and endangered animal species rely on riparian environments; in the western United States, 80 percent of all animal species depend on riparian environments for survival and reproduction (Coyle 1988, 7). Therefore, rivers occupy a pivotal position in many federal decisions related to endangered species, and river science is increasingly being asked to supply data, explanation, and predictions of river behavior for the benefit of species protected by the act. Riparian birds such as the southwestern willow flycatcher (Marshall 1995), inland native fishes such as the Colorado River squaw fish and humpback chub (Collier, Webb, and Schmidt 1996), and anadromous fishes such as salmon in Pacific and Atlantic coastal streams presently demand improved knowledge about river processes (Lackey 1999). The recovery of these endangered species depends on the maintenance of the physical integrity of specific rivers. Decisions about necessary measures to recover these species will affect millions of human users of water resources, so that the interaction between protected threatened or endangered species and the rivers they depend upon is likely to continue to be a contentious component of public policy debate.

Dams are becoming a prominent part of the endangered species debate because dams adversely affect the aquatic or riparian ecosystems for these species (Figure 9). General interest in removing or modifying dams derives not only from their environmental impacts but also from questions about their safety and their effectiveness in promoting their original intended functions. Effectiveness is especially at issue with regard to utility of flood control structures. Although the federal govern-

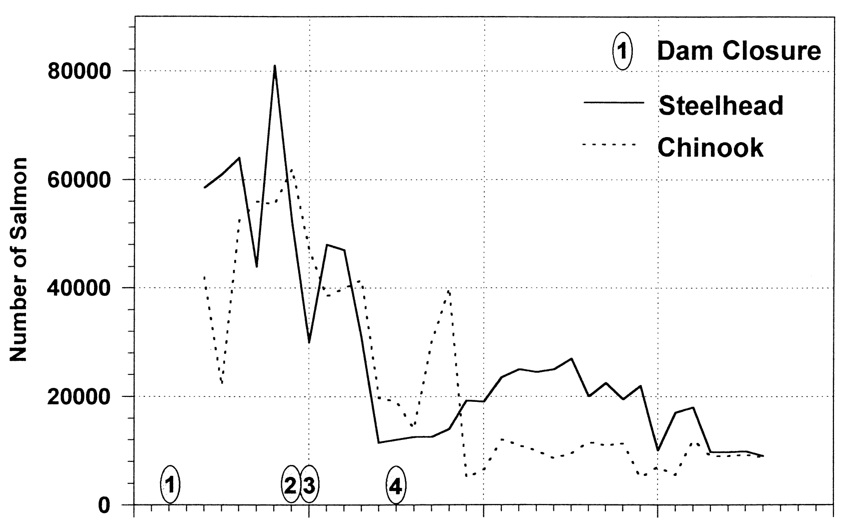

Figure 9. The decline in numbers of summer steelhead and spring/summer chinook salmon in the middle Snake River, Idaho, and the dates of closure for the four major dams on the lower Snake River: (1) Iceharbor Dam, (2) Lower Monumental Dam, (3) Little Goose Dam, and (4) Lower Granite Dam. Unpublished data from fish surveys by the state of Idaho.

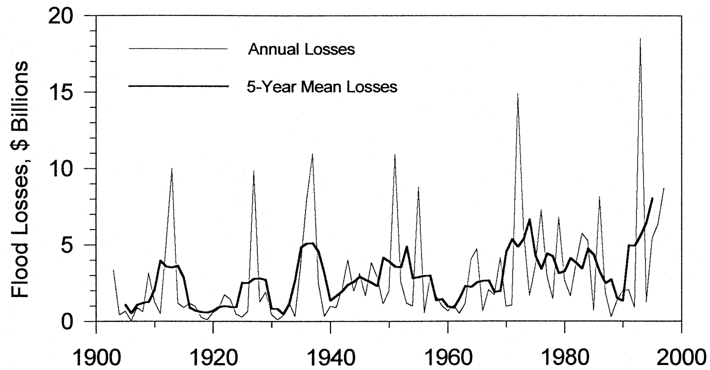

Figure 10. Graph showing annual and five-year running mean losses from flood damage in the United States. Despite massive investments in flood reduction, losses have gradually increased because of encroachment into hazardous areas. Data from National Weather Service (1999).

ment has spent more than $30 billion since 1936 on flood control measures, the losses to floods in this century total more than $280 billion, with the mean annual losses continuing to increase (Figure 10; National Weather Service 1999). In many cases, the increase in losses represents unwise occupation of flood plains and failure to avoid hazardous zones. For every $5 in public funds spent in flood protection, the private sector spends $6 to develop hazardous locations (Hanke 1972, cited by Costa and Baker 1981). A reliance on dams for flood protection is obviously only a partial solution, and nonstructural alternatives with fewer environmental costs are warranted.

As dams continue to age, safety is becoming an important concern. Engineering surveys have classified 32 percent of all dams in the nation as posing "significant" or "high" downstream hazards (U.S. Army Corps of Engineers 1996). Public policy for dams pivots on the balance between economic benefits and environmental costs, while scientific issues focus on the downstream effects of dams and the unknown consequences of their removal. Dams offer important opportunities, however, because they are partial control valves on river discharges and can provide experimental flow regimes, including small artificial floods. Re-engineered structures and modified operating rules can improve downstream naturalness and physical integrity without completely sacrificing the original purposes for the dams.

Dams originally built for limited purposes such as flood control or navigation usually operate under multiple objective principles. These operating rules offer the possibility of accommodating new objectives, including improvement of downstream physical integrity, habitat maintenance for endangered species, and recreation. Changes in operating rules for dams in the Missouri and Columbia river systems are ongoing examples that show the political volatility and economic implications of such adjustments.

The removal of dams is not a new idea. In the 1830s Thoreau ([1849] 1961, 42) advocated the use of a crowbar to destroy a dam on the Concord River at Billerica, Massachusetts, to improve spawn habitat for anadromous fishes. Since 1912, 467 dams have been removed throughout the United States, though most of them have been relatively small (American Rivers, Inc., Friends of the Earth, and Trout Unlimited 1999). The greatest number of decommissions has been in Wisconsin, often to improve downstream fish habitat. The most widely debated and publicized removal thus far has been that of the Edwards Dam on the Kennebec River, Maine, in 1999. Additional dams formally slated for removal include Glines Canyon and Elwha Dams on the Elwha River, Washington (discussed above), and Condit Dam on the White Salmon River, Oregon.

Re-engineering of structures, changes in operating rules, and removal of dams reflect logical changes in socially defined goals for rivers and their technology. When dams were built decades ago, they were constructed to solve particular problems using then existing technology, without knowledge of the environmental consequences. With improved knowledge now available about these unforeseen effects, both the public and professionals are modifying their perceptions of dams and searching for ways to reduce their negative impacts.

Recommendations

The foregoing review leads to a series of summary recommendations for science and policy directed towards improving the physical integrity of America's rivers. The recommendations outlined above do not require new legislation at any level of government. Rather, their implementation depends on adjustments to the application of existing laws and policies. The recommendations can be actuated through planning efforts, guidance documents, operating rules, management strategies, and research agendas.

- Reduce *fragmentation* of rivers by changing operating rules for some dams to include the maintenance of downstream environmental quality, re-engineering some dams for downstream objectives, and removing antiquated or unsafe dams.
- Improve the *physical integrity* of rivers under provisions of the Clean Water Act by including in policy the concept of physical integrity as an equal partner with biological and chemical integrity.
- Include *functional physical systems* as parts of a conceptual framework for research and policy efforts.
- Use the *indicator parameters* of channel width, water discharge, channel pattern, and channel sinuosity in measurement and monitoring programs for adaptive management of rivers.
- In basic research, emphasize explanations of why rivers *change* rather than their tendency toward hypothetical equilibrium states. In decision making, create policies to emphasize human accommodation to change rather than trying to exert complete control of rivers.
- Preserve as much as possible of the tiny amount of remaining rivers that is in a pretechnological condition. In restoration efforts, address *naturalness* by specifying goals that are scientifically reasonable and socially acceptable.
- In research and policy predictions, forecast the locational characteristics of rivers using *probabilistic* methods rather than relying on absolute certainties.
- Organize policy making for rivers according to regions that are *watersheds*.
- In funding research and building policies for river preservation and restoration, insure *geographic representativeness* by including all regions of the nation.

Conclusions

America's rivers are not simply water. They are complex geographical spaces that have also provided transportation, mechanical and electrical power, water resources, waste disposal, wildlife habitat, recreation space, and contributions to the quality of the nation's aesthetic life. In our efforts to capitalize on these varied resource values and to protect ourselves from river hazards, our society installed thousands of dams that forever changed the dynamic components of a once natural system. We can never completely restore the original conditions, and even if we could we would not want to do so everywhere. In many places, however, we can and should improve the physical integrity of our rivers.

A century and a half after he wrote it, Melville's observation is still true: there truly is magic in rivers and their waters. That magic, an American legacy, is partly real and partly a cultural myth, but it is worthy of the social, scientific, and financial capital required for its restoration, maintenance, and preservation. We may be the only country that has a short enough history of technological impacts on our rivers and enough wealth to be able to restore a significant amount of what we have lost. A century from now, the United States may be one of only a few countries—perhaps the only country—where uncontaminated, somewhat natural streams survive. If we make the right choices now to establish physical integrity as part of our science and policy in the early twenty-first century, we will realize a truly great legacy for American rivers in which those streams are productive components of vibrant economy, continuing threads of a rich cultural heritage, and quality natural environments for all people for many generations to come.

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Correspondence: Department of Geography, Arizona State University, PO Box 870104, Tempe, AZ 85287-0104, email graf@asu.edu; after July 1, 2001, Department of Geography, University of South Carolina, Columbia, SC 29208.