Aquatic Ecosystems Symposium

Organized and Edited by
W.L. Minckley
Arizona State University
Tempe, Arizona

Report to the Western Water Policy Review Advisory Commission

The Western Water Policy Review Advisory Commission

Under the Western Water Policy Review Act of 1992 (P.L. 102-575, Title XXX), Congress directed the President to undertake a comprehensive review of Federal activities in the 19 Western States that directly or indirectly affect the allocation and use of water resources, whether surface or subsurface, and to submit a report of findings to the congressional committees having jurisdiction over Federal Water Programs.

As directed by the statute, the President appointed the Western Water Policy Review Advisory Commission. The Commission was composed of 22 members, 10 appointed by the President, including the Secretary of the Interior and the Secretary of the Army, and 12 members of Congress serving *ex-officio* by virtue of being the chair or ranking minority member of the 6 congressional committees and subcommittees with jurisdiction over the appropriations and programs of water resources agencies. A complete roster is provided below.

This is an Independent Report to the Commission

The report published herein was prepared for the Commission as part of its information gathering activity. The views, conclusions, and recommendations are those of the author(s) and are not intended to represent the views of the Commission, the Administration, or Members of Congress serving on the Commission. Publication by the Commission does not imply endorsement of the author's findings or recommendations.

This report is published to share with the public the information and ideas gathered and considered by the Commission in its deliberations. The Commission's views, conclusions, and recommendations will be set forth in the Commission's own report.

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Policy Review Advisory Commission

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The presenters, authors, contributors, and especially the organizer of this symposium thank them all, and the last takes responsibility for any errors or misinterpretations that may exist in written contributions.

ACRONYMS AND ABBREVIATIONS

Acronyms in text in addition to standardized designations for States are as follows: **ACE**, U.S. Army Corps of Engineers; **BLM**, U.S. Bureau of Land Management; **BOD**, biological oxygen demand; **BR**, U.S. Bureau of Reclamation; **C**, carbon; **DOI**, U.S. Department of Interior; **EPA**, U.S. Environmental Protection Agency; **ESA**, Endangered Species Act of 1973, as amended; **Fe**, iron; **FEMA**, Federal Emergency Management Administration; **FERC**, Federal Energy Regulatory Commission; **FS**, U.S. Forest Service; **FWS**, U.S. Fish and Wildlife Service; **GS**, U.S. Geological Survey; **HCP**, Habitat Conservation Plan; **LTER**, Long-term Ecological Research site (NSF); **MOU**, memorandum of understanding; **N**, nitrogen; **NEPA**, National Environmental Policy Act; **NGO**, Non-governmental Organization; **NAM**, National Monument; **NP**, National Park; **NWR**, National Wildlife Refuge; **NAS**, National Academy of Sciences; **NAWQA**, National Water-quality Assessment Program; **NBS**, U.S. National Biological Survey (Service); **NRCS**, U.S. Natural Resource Conservation Service; **NPS**, U.S. National Park Service; **NMFS**, U.S. National Marine Fisheries Service; **NRC**, National Research Council; **NSF**, National Science Foundation; **P**, phosphorus; **RIP**, Recovery Implementation Plan; and **TNC**, The Nature Conservancy.

Scientific names of plants and animals in text (excluding microorganisms and domestic livestock) are in an APPENDIX.

CONVERSION TABLES

Area

Square feet (ft^2) X 0.093 = Square Meters (m^2) X 10.77 = ft^2
Acres X 0.405 = Hectares (ha) X 2.471 = acres
Square Miles (mi^2) X 2.592 = Square Kilometers (km^2) X 0.386 = mi^2

Distance

Inches (in) X 2.540 = Centimeters (cm) X 0.394 = in
Feet (ft) X 0.305 = Meters (m) X 3.281 = ft
Miles X 1.610 = Kilometers (km) X 0.621 = mi

Mass

Parts Per Million = Milligrams/Unit Weight or Volume (e.g., $mg.l^{-1}$)
Pounds (lbs) X 0.454 = Kilograms (kg) X 2.205 = lbs

Volume

Cubic Feet Per Second (cfs) X 0.028 = Cubic Meters Per Second ($m^3 \cdot s^{-1}$) X 35.714 = cfs
Acre Feet (af) X 1233.49 = Cubic Meters (m^3) X 8.107 X 10^4 = af

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PRESENTER:

William L. Graf is Regents' Professor of Geography at Arizona State University. He obtained his Ph.D. from the University of Wisconsin, majoring in physical geography and a minor in water policy for public land and water. The focus of his geomorphologic research and teaching has been on river-channel change, human impacts on river processes and morphology, contaminant transport and storage in river sediments, especially in dryland rivers. In the area of public policy he has emphasized interaction of science and decision-making, and resolution of conflicts between economic development and environmental preservation. His research has been funded by Federal, State, and Local agencies, ranging from NSF, EPA, and ACE, to cities, Native American tribes, and private companies. Dr. Graf has published more than 100 papers, articles, book chapters, and reports; his books include "Geomorphic Systems of North America," "Fluvial Processes in Dryland Rivers," "Wilderness Preservation and the Sagebrush Rebellion," and "Plutonium and the Rio Grande." His work has received awards from the Association of American Geographers and the Geological Society of America, as well as a Guggenheim Fellowship. He has served the NAS/NRC in numerous capacities, including membership on the Water and Science Technology Board, Committee on Glen Canyon Environmental Studies, Committee on Rediscovering Geography, and Chairing the Workshop to Advise the President's Council on Sustainable Development as well as the Committee on Innovative Watershed Management.

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WESTERN RIPARIAN ECOSYSTEMS

PRESENTER:

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SUSTAINABILITY OF WESTERN WATERSHEDS: NUTRIENTS AND PRODUCTIVITY

PRESENTER:

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SUSTAINING WESTERN AQUATIC FOOD WEBS

PRESENTER:

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SUSTAINABILITY OF WESTERN NATIVE FISH RESOURCES

PRESENTER:

James E. Deacon is Distinguished Professor and Chair of the Department of Environmental Studies at University of Nevada, Las Vegas. He received his Ph.D. from the University of Kansas with a major in Zoology. Since arriving at Las Vegas in 1960 his research has focused on ecology and conservation biology of desert fishes, funded by a variety of agencies and organizations such as NSF, EPA, NPS, FWS, TNC, etc. He has published more than 70 scientific articles, papers, and contributions to books and other compendia, and has received awards from American Fisheries Society, National Wildlife Federation, NV Department of Museum and History, and others. He has served as expert witness in water-rights litigation and adjudication proceedings at both State and Federal levels, and has been involved in developing recommendations for water-quality standards and flow criteria essential to maintenance of ecosystem health and endangered fishes in Western waters. His work has been influential in creation of two National Wildlife Refuges, establishing the extent of reserved Federal water right for two National Parks, development of "return flow credit" concepts in allocating waters of the lower Colorado River, designation of several species of threatened and endangered species, and a jeopardy opinion leading to denial of application for dam construction in the Virgin River system.

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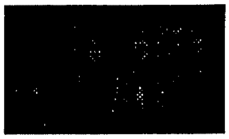

CHAPTER I: INTRODUCTORY REMARKS

BY

W. L. MINCKLEY

Recent reviews of the status of the World's fresh-water supplies all forewarn of bad times coming (1-2, 7, 13). World demand for fresh water is increasing disproportionately to human population increases in developed countries and population increases are disproportionate to water availability in underdeveloped ones. Essentially none of the projections for future fresh water needs is sustainable (9, 10). Indeed, current demands are not sustainable in arid or even semi-arid areas, and things like over-pumping of groundwater aquifers, interbasin transfers, long-distance transport, and other means of augmenting scarce water supplies are already widely practiced. Ecosystem disruption caused by unsustainable practices, as in the Aral Sea basin (9), is a critical factor, broadly damaging economy, community, and human health. And ecosystem disruption, largely from deforestation over a huge area of South China for example (3), resulted in desertification and intensification of the annual flood-drought cycle, with serious adverse effects on crop production, economy, and clearly on the natural ecosystem.

Much of western United States is in no better shape than the rest of the World. Even though this Nation may be more sensitive than others to the reality that economic well-being depends on ecosystem well-being, unsustainable practices continue to pervade our values and practices and therefore our laws and regulations. Government encouragement of unsustainable water development has permitted what we now recognize as a catastrophic decline of the Ogallala and Edwards aquifers of the High Plains and central TX, respectively, over-apportionment of the Colorado River, and biodiversity altering dam construction on all major rivers (5, 7, 11). Surface water resources are developed, groundwater supplies are being depleted, and the watersheds upon which both of these depend, channels that carry water toward the sea, the biota that keeps aquatic ecosystems on track (1, 12), and the water itself all are badly mistreated. Without reliable water, "sustainable development" in the arid Western USA is an oxymoron.

Definitions of sustainability differ substantially among the human users of Earth's ecosystems. That proposed by the World Commission on Environment and Development (13), an "ability to meet the needs of the present generation without compromising the ability of future generations to meet their needs," is perhaps nearest the definition used here. Although intended for humans, it applies as well to other organisms that both help to operate and operate within the biosphere. The difference is that although humans can and sometimes do respond like other animals by migrating, reducing their reproductive rate, or dying off, they more often do not. Technology is applied to get more of whatever comes into short supply, thereby avoiding the issue and passing it on to future generations. Unfortunately, human development that gets around resource limitations often "overshoots" the initial solution, and demands continue to escalate. Much of modern society is finally realizing that traditional Earth resources are finite and that even renewable resources like water and biological commodities must be nurtured if they are to remain available for use. Hence the recent urgings for integrated research on both natural and artificial aquatic systems (4, 7-8), and organization of symposia such as this.

Information precedes informed decision, so with first contacts for this symposium a decision was made to approach the past, current, and projected future state of Western USA surface waters by pursuing the perspectives of active research scientists relative to six highly interwoven ecosystem categories:

- Watersheds: the landscape from which water flows on the surface or underground to accumulate in channels as streams, in surface depressions as lakes, or as groundwater aquifers.

- Channels: the collecting and transporting conduits through which surface water and its contents move and are moved from watershed landscapes to the sea.

- Riparian zones: the land-water interface or ecotone through which aquatic and terrestrial systems interrelate and interact.

- Primary producers and primary production: the means by which solar energy and nutrients are combined to produce organic matter, the use of which forms the basis for ecosystem functions.

- Secondary producers and secondary production: the organisms that use primary production, translating and combining it through food webs to levels most often used by humans and other consumers.

- Native fishes: an example of a large, well-known group of animals subject and highly sensitive to changes in Western aquatic systems thus reflecting in their status the state of ecosystem health.

The charge from the Committee was to define the critical resources of the ecosystems or ecosystem components discussed; relate what is happening to these resources today in terms of their health, stability, etc. in the American West; delineate why we should be concerned; and recommend ways to help. The final result was production of five independent documents prepared by five independent groups of research scientists. Watersheds, the basis for conservation and restoration of all aquatic systems (6), was incorporated early into each of the other accounts and therefore was not adddressed in a separate document.

It might have been preferable to summarize the status of the various interactive and interwoven components of aquatic ecosystems in a single integrated report. Keeping the subjects separate, albeit artificial, served to focus reviews of literature and use of examples, however, and redundancy emphasizes the complex and interactive nature of aquatic ecosystems. Redundancy in interpretation of kinds of and reasons for environmental changes and their impacts on the various ecosystem components goes even further in assisting in definition of major problems that exist. Further, the overlapping statements of issues and recommendations for dealing with these problems underline the unanimity of contributors on where, when, and how degradations occurred and what actions are needed to correct them.

It is important to stress that the independent conclusions of all five contributions are unanimous and unequivocal. Aquatic systems in the American West are broken and must soon be fixed if they are to again be sustainable. Western watersheds are degraded not only in forested areas but throughout the entire region, which has resulted in major stream-channel changes that, in turn, are reflected in severe deterioration in biological conditions. Dams and associated development have had further, profound, and negative impacts, also reflected directly in significant biological change. Finally, intentional and unintentional biological manipulations, particularly the introduction of non-native organisms, are orchestrating the final blows that result in substantial losses in natural biodiversity.

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CHAPTER II: SUSTAINABILITY AND CHANGING PHYSICAL LANDSCAPES

BY

WILLIAM L. GRAF, WITH KATHRINE K. HIRSCHBOECK, RICHARD A. MARSTON, JOHN PITLICK, AND JOHN C. SCHMIDT

Introduction

After more than a century of western water policy fostering development of water as a commodity, modern American social values are changing to emphasize an ecosystem perspective. We have come to treasure not only the water that fuels the engine of economic prosperity, but also the landscapes of our western rivers and watersheds. This new emphasis challenges decision makers to take a more complicated view of the resource than in the past. The purpose of the following discussion is to outline the physical basis of the western aquatic system, especially its geomorphology and hydrology, by exploring the historic condition of watersheds and rivers, defining their present condition, identifying the scientific and policy issues that have evolved for these resources, and suggesting future policy initiatives to enhance the sustainability of the western aquatic system.

The importance of this review derives from established policy and from our scientific understanding of the way the environmental systems work. The Federal Water Pollution Control (or Clean Water) Act of 1977 specifies the objective of the law is "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters (33 U.S.C.A. §§ 1251-1387)." Other important legislation related to the physical integrity of watersheds and rivers includes the Rivers and Harbors Act of 1899 (33 U.S.C. 401), which gives permitting authority to the ACE over any activities that affect physical characteristics of the nation's navigable waterways. In addition to numerous laws authorizing engineering works to change river configurations, the Wild and Scenic Rivers Act (16 U.S.C. 1271) injected preservation objectives into the management of streams by stipulating that certain river reaches "shall be preserved in free-flowing condition and that their immediate environments shall be protected." Heretofore, much scientific and regulatory attention has focused chemical and biological issues, but despite its stated importance in law, the issue of physical state has been less prominent. The sciences of geomorphology and hydrology offer administrators a set of concepts as well as field and other techniques to address this deficiency (22).

The physical components of the western aquatic ecosystem, their watersheds, lakes, and streams, consist of the climatic system and the topographic landscape along with water, sediment, and energy they produce (9). These components provide the stage upon which western life is played out. The climate and highland watersheds are the sources of water in the system, while the rivers are the conduits of the resource. River waters, sediments, and landforms provide the environmental framework for valued aquatic life and unique riparian ecosystems that are linchpins in the terrestrial ecosystem. Attention only to the chemical and biotic characteristics of these landscapes will not insure sustainability. Policies and management strategies that include consideration for the landforms, water, sediment, and energy foundations of the system are critical controls we can exert to improve the long-term health and productivity of the systems.

Historic Physical Conditions and Policies

Precipitation, falling mostly in high mountain areas, provides a basic input of moisture to the entire western ecosystem, but its delivery by atmospheric processes has been remarkably unstable and unevenly distributed. Although engineers and planners would prefer a constant supply of moisture and construct their understanding of the system on the concept of "stationarity" (in which hydrologic conditions are assumed to be unchanging), the natural reality is a climatic system that flip-flops between two fundamental behavior patterns: those observed in El Niño and La Niña years (Box 1). In one case, sea-surface temperatures, atmospheric-pressure systems, and jet-stream alignments produce wet years and flooding in the southwest with dry conditions in the Northwest. In other years the reverse arrangement occurs. Superimposed on these changes are longer-term adjustments that have resulted in as many as half a dozen distinct hydroclimatic periods in the past century (13). These hydroclimatic changes then ripple through the conditions in watershed and river components of ecosystems, to be ultimately reflected in aquatic and terrestrial biologic behavior as well as the quantity and quality of the basic water resource.

(Box 1) ***Western Hydroclimatology, Floods, and Droughts, by Katherine K. Hirschboeck.***

The ultimate source of the water in western rivers and watersheds is the atmosphere. Through the dynamics of large-scale atmospheric circulation processes that are global and hemispheric in scale, moisture is evaporated from ocean surfaces and delivered to the American West by episodic events. Variations in atmospheric circulation determine the geographic distribution, intensity, duration, and timing of the precipitation that controls streamflow. Western water policy is an accommodation to that timing and geography. Flood hydroclimatology, paleoflood hydrology, and tree-ring analysis can reveal extreme events and their patterns on time scales exceeding the length of stream-gage records.

Through flood hydroclimatology, analysts can identify the particular atmospheric circulation patterns that are likely to produce major flood events (13). For example, the most extreme floods in large river basins of central AZ are products of a serial progression of winter storms steered into the State along an anomalous southerly storm track (14). The December 1992-February 1993 floods in the Verde River are examples. Large basins in the southern part of the State, however, have floods produced largely by dissipating tropical storms generated off the west coast in summer and fall. These arrangements explain the October 1977 and October 1983 floods on the Santa Cruz River, AZ. Paleoflood hydrology can extend the knowledge gained from gage records by interpreting deposits left by prehistoric events. The location of these deposits permits reconstruction of depths of flow during the events, and buried materials containing carbon allows them to be assigned dates of deposition (7). Tree-ring records provide long-term information about droughts, because the wide and narrow rings of climate-sensitive trees record climatic changes over thousands of years. A 7979-year reconstructed record for precipitation over the Great Basin from 6000 B.C. to A.D. 1979 shows two prolonged droughts that, if they were to recur in modern times, would wreck havoc with western water management (15).

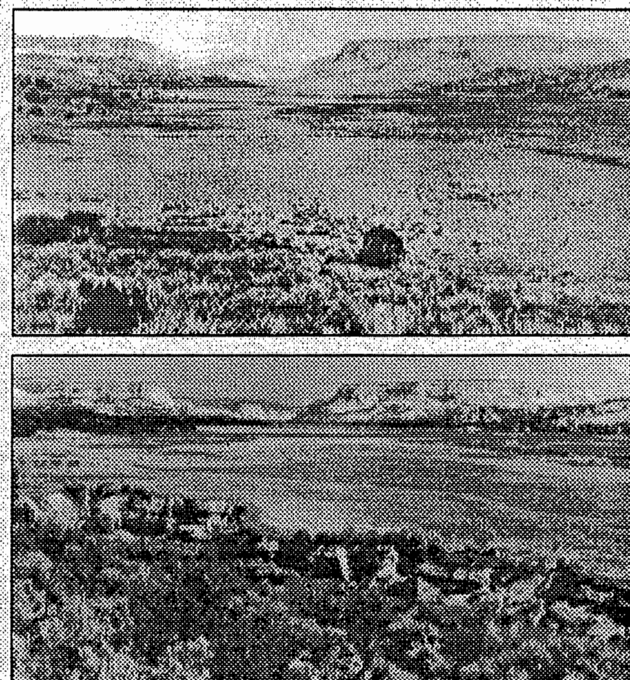
Problems arise when extremes occur in the water-delivery processes to create floods or droughts. The extreme behavior originates from anomalous atmospheric circulation patterns such as shifting storm tracks and persistent high- or low-pressure systems. These anomalies can recur on variable temporal and spatial scales. Some are linked to the El Niño/La Niña variations in the tropical Pacific Ocean, but others are related to unique spatial patterns of ocean-surface temperatures and atmospheric circulation that recur on decadal or longer time scales. Because these anomalous circulation patterns are infrequent, our relatively short stream-gage records do not adequate describe their effects, and our knowledge of the full range of hydrologic extremes is limited.

Examples of this non-stationary hydroclimatic behavior include radical changes that occurred at the beginning of the twentieth century in the American Southwest. After huge regional floods in the early 1890s, the region's watersheds and rivers experienced severe droughts that contributed to the decline of vegetation cover on upland areas and significant stress in riparian systems (5). Many rivers became dry for portions of each year in the first few years of the twentieth century. Water resources for economic expansion became so limited that they provided a stimulus for major policy changes, including the passage of the Newlands Act which created the Reclamation Service (later the BR) in 1902. In 1905, however, the hydroclimatic system adjusted and produced some of the largest floods of record. The lower Colorado River, overburdened by the immense amounts of runoff, burst its banks in the vicinity of canal headgates near the USA-Mexican border, causing a two-year diversion of most of the river's flow into the Imperial Valley, resulting in initiation of the modern version of the Salton Sea (31).

In addition to fundamental changes in atmospheric inputs, western watersheds and rivers experienced radical changes during the last century in other control factors directly related to human activities. These changes may be considered across a scale continuum, ranging from the small headwater drainage basins, to intermediate-sized valleys, and finally to the large regional rivers. The upland drainage basins of the West are the region's primary water source, so that minor adjustments in their surface conditions have substantial and widespread effects. Throughout the western states, for example, grazing has reduced the density and changed the composition of plant cover in almost every headwater drainage basin. As a result, runoff is greater than it originally was under natural circumstances, floods are larger and more frequent, and more sediment is produced that is washed down the slopes into the small first-order channels. In a 20-year GS study in western CO, for example, it was demonstrated that grazed watersheds experienced about a third more runoff and in some cases twice as much erosion as similar ungrazed watersheds (23). Logging, especially clearcutting, causes similar changes in water and sediment yield from headwater basins. The sum of eight years of research by the FS, particularly at Wagon Wheel Gap, CO, and Sierra Ancha, AZ, demonstrated that not only are water yields, sediment yields, and flood peaks increased by a quarter to a third, but timing of the flows was altered, with high flows occurring earlier in the year (20). Nutrient yields also measurably decrease from logged watersheds. Headwaters impacts are not limited to extractive industries, however. Urban expansion causes increased sedimentation during construction followed by increased flood flows (8, 12), and off-road vehicle use dramatically alters runoff and erosion processes by reducing by more than half the ability of the land surface to absorb rainfall (27).

While human impacts on upland watersheds were progressing, additional impacts changed conditions along larger streams (Fig. 1). Road and railroad construction on valley floors altered channel locations and contributed to a potential for focusing the erosive power of flowing water on restricted areas. The collision of these forces with occasional major floods resulted in eroded upland slopes, caused widespread arroyo cutting (channel entrenchment), and destroyed valley marshlands (ciénegas) during the period between about 1880 and 1910. A flood of sediment inundated downstream agricultural areas. In several parts of the West, mining activities discharged vast amounts of waste rock into mountain streams that transported debris into valleys below, causing widespread damage. As an example, the region near Sacramento, CA, is still dealing with the implications of mining waste in the American River a century later (16). Elsewhere, water diversions from channels, especially on the western Plains, resulted in drastic shrinkage of stream channels and irreversible ecological impacts. Diversions from the Platte River, NE, for example, have resulted in the expansion of riparian woodlands to the exclusion of the original, natural conditions of open-water marsh vegetation critical for wildlife (17, 29).

In some instances, human impacts have been circuitous and difficult to assess, but nonetheless pervasive and of large magnitude. The removal of beaver illustrates these indirect effects (2). From about 1820 to 1850, the beaver-pelt market in Europe stimulated relentless trapping in Western America's rivers by Anglo-Europeans and Native Americans. Virtually every stream and river in the region contained at least some beaver at the beginning of the Nineteenth century, but by mid-century when beaver hats had gone out of fashion and the market had collapsed, they were essentially exterminated. When they flourished, beaver constructed uncounted thousands of small dams and ponds on small upland streams throughout the West. These structures retarded the downstream movement of water, temporarily stored sediments, organic materials, and nutrients, and reduced flood peaks by attenuating them through small-reservoir storage. The animals also accumulated woody debris on the banks of larger streams, increasing bank stability. When the beaver disappeared, so did their small engineering works along with their beneficial hydrologic effects.

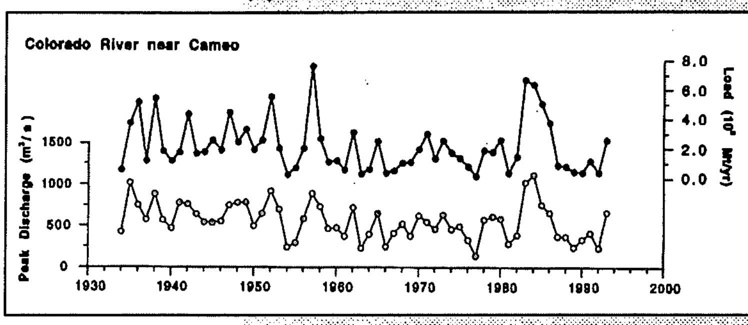


(Figure 1) Historic changes in a typical interior western watershed. View upstream of Johnson Canyon south of junctions with Needle and Flood creeks, southern UT, showing changes between 1872 (top) and 1984 (bottom). Between the two dates the vegetation cover on the valley floor became substantially less, woody vegetation invaded the foreground hillslope, and a 6-m-deep arroyo was eroded into the alluvial fill with attending reduction in groundwater levels. Top view, 1872 J. K. Hillers photograph 1272, GS Photo and Field Records Library, Denver. Bottom view, 1984 W. L. Graf photograph.

Changing hydrologic conditions on western rivers over the past century were dramatically accelerated by construction, maintenance, and operation of high dams (Box 2). These structures succeeded in their initial objectives of reducing flood peaks, reducing monthly and annual variation in discharge

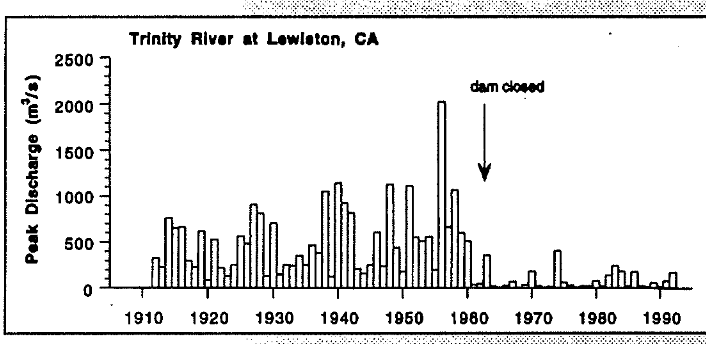
(Box 2) ***Effects of Dams, Colorado and Trinity Rivers, by John Pitlick.*** *It is a river's job to carry water, sediment, and nutrients from the basin it drains. If the natural flow of water and sediment is interrupted by construction of dams, we can expect the river to adjust its characteristics in some way. A common trend in western USA is that rivers often tend to become narrower downstream from dams (30). Channel narrowing reduces the capacity to convey large floods, and decreases amount, quality, and diversity of habitats used by fishes and other aquatic organisms. Here, we take a closer look at two rivers exemplifying changes that can take place once a dam or series of dams are in place, and the effects that these changes can have on native fishes.*

The Colorado River has many small-to medium-sized reservoirs in its upper basin; built mostly in the 1950s and 1960s for flood control, storage, and water supply. Collectively these reservoirs have had system-wide impacts. The figure below shows annual trends in the peak discharge and sediment load near Cameo, CO. Note how they generally mimic each other, and note the distinct period from 1958 to 1982 when annual loads were about 40% lower than the long-term average.

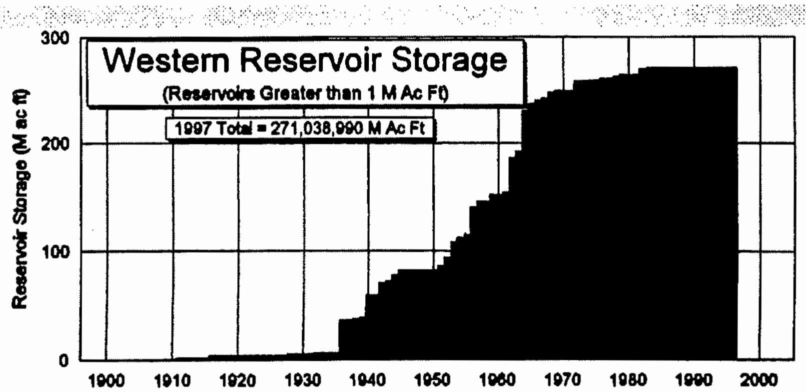


These trends are a direct consequence of dams which store runoff in the spring and released it later in the year when water demands are higher. Dams in the upper Colorado do not trap much sediment, however, because most of it comes from erodible areas further downstream. Thus, sediment from unregulated tributaries continues to enter the mainstem, more or less as always, but the river has lost its ability to carry the load because high flows are less frequent now than before the dam-building era. The net effect is sediment accumulation and channel narrowing. Studies have shown average width of the river has decreased about 30% in reaches near Grand Junction, CO (24), considered critical habitat for Colorado squawfish and razorback sucker, two Federally listed endangered species. There is sound evidence of substantial habitat loss, and losses coincide with the period when most reservoirs were built.

The Trinity River in northern CA has undergone similar hydrologic-geomorphic changes, with equally significant impacts on native chinook and silver salmon, and steelhead trout. Trinity and Lewiston dams were constructed in the early 1960s as part of the BR Central Valley project. As shown in the figure below, they had a significant effect on annual peak discharge.



Not far downstream, an unregulated tributary named Grass Valley Creek joins the Trinity. It drains a basin underlain by a weathered granite that rapidly breaks down into its constituent mineral grains (sand-sized particles called "grus"). This sand enters the Trinity, but cannot be transported far downstream because released flows from the dams are kept low. As a result, sand accumulates in interstices of gravel where salmon and steelhead lay their eggs. If the interstices fill completely, fry cannot emerge from the streambed and die. Several years ago an attempt was made to "flush" sand from the streambed by releasing a week-long flood from Lewiston Dam. Although water used in this trial could be viewed as a lost commodity, the experiment effectively restored quality of certain gravel-bar habitats (see 19 and 28 for further information on this project and related issues).

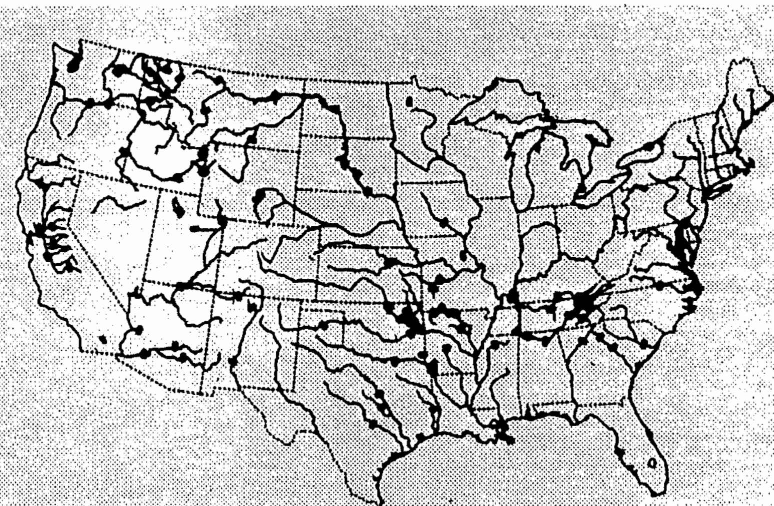


(Figure 2) Storage volumes in western reservoirs with greater than a million acre feet capacity each, a direct measure of the hydrologic disruption of regional rivers.

through reservoir storage, and generating hydroelectric power. As social values changed to include new objectives for the dams and reservoirs, hidden costs of the earlier achievements became more obvious. Salmon spawning grounds on streams of the Pacific Northwest, for example, were blocked, while the operating rules of others prevented maintenance of gravel-bed streams free of fine sediments during the spawning season. The lack of natural floods downstream altered the recreation potential of streams by permitting accumulation of impassable rapids, as well as fostering new, unnatural ecosystems not attuned to large annual floods. Hydropower operations caused rapid fluctuations in river levels downstream, eroding valuable beaches, altering fish habitat, and destabilizing riparian ecosystems. In the Grand Canyon, the Colorado fluctuated as much as 4.0 m each day (3).

Construction of large dams (those with storage capacities of greater than one million acre feet) on western rivers began in the early twentieth century, but was dramatically accelerated during the period from about 1950 to 1970. By the end of the construction era in 1984, 70 such structures impounded more than 271 million acre-feet of water in western American rivers (Fig. 2). When effects of these dams are added to impacts of hundreds of structures storing 100,000 acre feet or more, profound and permanent changes in regional river landscapes were inevitable. The inundation of valued agricultural land and riparian habitat by reservoir waters is accompanied by widespread downstream effects including reduced flood frequencies and magnitudes, altered low flows (sometimes increased, sometimes decreased to zero), reduced sediment and nutrient loads, changes in channel-sediment characteristics (especially particle size and mobility), expanded and stabilized channel bars, shrunken channels, changes in channel patterns, and deactivation of floodplains (Box 3). These effects are especially prominent in western rivers because the West is the location of the majority of the large dams (Fig. 3).

The net result of dams on western rivers is that streams have been changed to a much greater degree than any adjustment anticipated by the influence of suspected global climatic changes. While global climate change has attracted much scien-



(Figure 3) Distribution of the 87 dams in the USA creating reservoirs with greater than a million acre feet each, showing their widespread impact on the West and Great Plains.

(Box 3) ***Sediment Dynamics and Beaches in the Grand Canyon, by John C. Schmidt.***

Thirteen years of research on geomorphology of the Colorado River in Grand Canyon, funded by the BR's Glen Canyon Environmental Studies program, demonstrate floods as critical natural process that have overwhelming impacts on riverine ecosystem health.

For decades, river managers were convinced that the daily range of high and low discharges from hydroelectric power generation was the sole determinant of persistent loss of sandbars in the Grand Canyon (18). These sandbars were a fundamental component of the pre-dam, natural-river landscape (26), and modern remnants are used by 22,000 river runners each year. However, adoption in 1991 of interim flow rules limiting the range of daily fluctuations did not completely stop sandbar erosion. They continued to decline in size and elevation by processes such as debris flows and gullying during intense rains. Observations of unregulated analogs to Grand Canyon like Cataract Canyon in Canyonlands NP showed that erosion is an inevitable process in all steep-gradient, narrow canyons dominated by debris fans and rapids, but that annual sediment-laden flows redeposit material and so rebuilt these bars. Collectively, the scientific community came to understand that only floods charged with sediment could replenish the sand inevitably lost from beaches and bars by erosion.

Release of an artificial flood of 45,000 cubic feet per second from Glen Canyon Dam beginning on 26 March 1996 was an unprecedented effort to confirm that controlled floods would indeed restore sand to eddies in areas of critical importance to managers. Preliminary results from the flood indicate that the goal was accomplished.

The frequency of future restoration floods will be dependent on tributaries that resupply sediment to the Colorado River downstream from Glen Canyon Dam. Research in Hells Canyon of the Snake River shows that frequent floods in the absence of sediment resupply scours sand from most eddies and banks (25). The Grand Canyon flood experiment nonetheless demonstrated that rivers can be restored within a context of careful management, monitoring, and controlled floods.

Elsewhere in the Colorado River Basin, flood releases can accomplish similar goals. The Green River channel in Canyon of Lodore, Dinosaur NM, has narrowed about 20% since the 1962 closure of Flaming Gorge Dam (11). The river corridor is overgrown by dense stands of vegetation, so only large flood releases are likely to restore the landscape specifically protected by expansion of the monument in 1936. Further downstream, large floods are needed to restore habitat for endangered native fishes. The Green and other western rivers (such as the Colorado, discussed above by Pitlick) depend on social acceptance of restoration floods to maintain a broad range of ecosystem functions in naturally dynamic rivers (4).

tific and policy attention directed toward assessing possible changes of as much as 5 to 20% in annual water yields and frequencies of large floods on western rivers, the USA has constructed enough reservoir capacity to store 325% of the average annual water yield of the entire country. In many western river systems, the storage impact has been as much as 400 to 500%. The frequency of large floods on many systems has been reduced to zero. Unlike global climate changes, these impacts of dams are not speculative or projected. Rather, over the past century they have become measurable attributes of the western aquatic system.

The present western watershed and river system is a mixture of conditions that range from natural to artificial (Table 1), with all gradations between (10). It is unlikely that many segments impacted by human activities will be restored to entirely natural conditions, and costs associated with moving a river segment the final step to natural configurations are usually prohibitive. In most instances the goal of restoration will be to move river segments no more than one or perhaps two incremental steps toward the natural side of the scale shown in Table 1, in many cases limited by the imposed hydrologic regimes.

Present Conditions and Policies

Present conditions in watersheds and rivers of the American West reflect the past century of hydroclimatic-and human-induced modifications. Upland watersheds that are the water source areas are variable: some high mountain drainage basins are nearly unchanged from their Nineteenth century arrangements and are in a wilderness state, but most basins bear the imprint of grazing, mining, logging, and recreational use. Their hillslopes presently shed more sediment than they did under entirely natural conditions, and small stream channels act as conduits for these materials to places downstream and at lower elevations. Downstream, this sediment is considered a pollutant in rivers, eventually coming to rest in artificial reservoirs and causing unwanted reduction in water-storage capacity.

Downstream from watershed source areas, western rivers have become physically segmented and disintegrated. Where once we had systems that conducted water, sediment, and energy downstream in a balanced sense on a century-long basis, we now have a geographically uneven system, with some parts dominated by storage, others dominated by ero-

Channel Type	Completely natural	Essentially natural	Partly modified	Substantially modified	Mostly modified	Essentially artificial	Completely artificial
Pattern, X-section shape, materials	No obvious evidence of human activities	→	Altered channel patterns, X-sectional shapes, or sediment	→	→	→	Completely engineered and/or built channel
Minor landforms	Same forms and processes found prior to humans	Altered by humans or changes in sediment	→	→	→	→	→
%Channel area engineered or disturbed	0	<10%	→	>10% <50%	>50% <90%	>90% <100%	100%
Descriptive notes	Completely undisturbed channel (e.g. "wild river")	Minor modifications in flow regulation or scatterd structures on an otherwise undisturbed channel	Obvious modifications by flow regulation of altered sediment supply = disturbed channel, scattered structures	Major modifications to channel forms and processes, up to half of channel area disturbed	→	Largely artificial channel due to engineered bed and/or banks; few natural forms remain	Channel completely determined by design with no natural forms
Example	Middle Salmon River, ID	Colorado River, Grand Canyon, AZ	Platte River, western NB	Potomac River, near Georgetown, PA	Santa Cruz River, near Santa Cruz, CA	Illinois River, central IL	Los Angeles River, Los Angeles, CA

Table 1. Geomorphic "naturalness" of river channels.

sion, and still others in an uncertain, changing status. Because of the hydroclimatic conditions, western rivers never operated on a continuous basis more typical of humid-region rivers, but in their natural state on a century-long time scale (or longer) they might have been considered to have achieved some sort of equilibrium operation across time and space. That equilibrium among water, sediment, energy, and riparian landforms no longer exists. Adjustments once facilitated by small- and moderate-scale floods cannot occur because of our water-control structures. Now such changes do not occur at all on many streams, or they take place during catastrophic spills from reservoirs that produce large, destructive floods. Our river processes are physical corollaries to what we see in fire regimes in western forests, where fire suppression has eliminated the small fires but has established conditions where very large, occasional fires are unnaturally destructive.

The policy structures of our Federal management efforts for these segmented river systems is equally fragmented. Some segments of rivers are controlled by flood management efforts by the ACE, others are under the direct influence of structures managed by the BR and some by Private or Local dam operators, and still others are impacted by management by the NRCS. Additional river segments have Federal management objectives defined by the Wild and Scenic Rivers Act emphasizing preservation. Coordination of these objectives with many goals for other agencies such as the FS, BR, NPS, and FWS increase the number of conflicts. What was once a single physical system without human management has become a divided system managed in bits and pieces by a balkenized governmental policy with competing objectives. Such an arrangement is not likely to provide long-term sustainability of the physical system and will inevitably result in short-term benefits for this generation at the expense of future generations.

Part of the problem of creating policy from science for watersheds and rivers is the lack of data about how the systems are operating (Box 4). If public agencies use adaptive management approaches wherein their actions are predicated on what they perceive in environmental processes, success depends on a flow of data about the systems. Established methods for collecting data about the physical properties of rivers are expensive. Ground-based survey of channel dimensions and characteristics is time-consuming and most useful if it can be done repetitively, although short-term funding often prevents such an approach. Sediment data are absolutely critical to understanding the dynamics of natural and impacted systems and to detecting changes in watershed integrity, but the expense of collecting data

(Box 4) ***Management of the Snake River, Grand Teton National Park, by Richard A. Marston.*** *The Snake River in Grand Teton NP, WY, provides an illustration of "complex response" in rivers, where an outside-induced change results in divergent geomorphic effects. The geomorphic changes in the Snake River trigger changes in river-related resources, some beneficial and some detrimental to Federal resource-management objectives. The river originates in Yellowstone NP, then flows southward through Grand Teton NP in a section renowned for its scenery, wildlife habitat, fisheries, and recreation, and where groundwater recharge and water supply are also significant considerations. The BR's Jackson Lake Dam, located in Grand Teton NP, provided irrigation water to ID farmers. The concrete dam, closed in 1918, raised the level of a natural lake by about 12 meters. In 1957, Palisades Reservoir was established downstream near the WY-ID border, allowing BR to alter the reservoir-release schedule for Jackson Lake Dam far upstream. Jackson Lake lost is role as a reservoir for storing irrigation water, and the magnitude and frequency of early summer peakflows downstream were greatly reduced.*

The impact of lower peak flows was to cause channel instability and floodplain disturbance. In limited reaches where sediment continued to be added from tributaries and eroding banks, the river aggraded and became more unstable because sediment-flushing flows had decreased. Meandering and braiding increased, and floodplain disturbance became more widespread due to channel shifting and overbank flows. The majority of the Snake River is not influenced by these sediment sources, however, and generally throughout its course in Grand Teton NP, it became more stable after 1957 because the erosional power had been reduced. Floodplain disturbance has become less common in most of these reaches.

The overall increase in channel stability and depression in floodplain disturbance resulted in changes to many river-related resources. The biodiversity of riparian vegetation at the landscape scale was increased. Older blue spruce forests expanded when floodplains became more stable and allowed a more terrestrial-like pattern of succession. The increase in blue spruce stands aided Bald Eagles and Osprey who use dead snags as nest sites. Biodiversity at the species scale has declined. Species-rich stands of willow and mountain alder, communities dependent on floodplain instability, have declined in favor of the relatively species-poor forest communities of cottonwood and blue spruce. Willow provides an important source of winter feed to the large moose population that occupies the floodplain. The safety of recreational boating has been improved because multiple-braided channels have been replaced by single-thread meanders, offering boaters fewer opportunities to select the wrong channel where canoes and rafts might be caught in snags or "strainers." Finally, small channels that had been valuable as spawning habitat have been abandoned on the floodplain now that floodplain disturbance is depressed, with eventual implications for Snake River cutthroat trout population.

on sediment concentrations in river waters is enormous (about $30,000 per year for a single monitoring station). A result of this expense is a precipitous decline in the amount of available sediment data on this key indicator variable, and in many river basins the amount of data being collected is insufficient to make informed decisions (Fig. 4).

Some fragments of the system are poorly or incorrectly represented in the Federal administrative view. The segments of rivers devoted to water-resource development are clearly and aggressively represented by BR or ACE, but the Wild and Scenic Rivers System, represented by various land-management agencies, is not yet complete. By definitions, the Nation has about 5.1×10^6 km (3.2×10^6 miles) of stream channels (21, p. 142), with 17% under reservoir waters. Human activities have altered all but about 2%, and the Wild and Scenic Rivers System permanently protects only about 0.3% (6). Although many river segments in the system are in the West, certain western environments are underrepresented. For example, the Colorado Plateau along with Basin and Range geomorphic provinces account for 13.7% of the land surface of the USA, yet they contain only 3.8% of protected rivers in the National Wild and Scenic Rivers System. In a more extreme case, the Great Plains occupy about 20% of the nation's surface, yet its historic and environmentally important streams account for only 2.8% of the protected rivers.

Issues and Recommendations

Current conditions present a series of unique challenges for establishing the sustainability of western watersheds and rivers. Maintenance and restoration of integrity of the physical system faces several issues, but action by the Federal government can provide the impetus for positive change and improve the prospects for sustainability.

ISSUE: Agency Organization.

Federal agencies for water resource management in the West are organized according to topic rather than geography. Local, Tribal, and State decision-makers bear an increasing burden of management problems, but they often do not have effective institutional structures or funding to deal with watershed and river basin issues that cross political boundaries. The ACE deals with flood control, the BR with water supply, the NRCS with agricultural implications, the FWS with life forms. Watersheds are physical integration systems, however, and require integrated management.

- ***RECOMMENDATION: Establish a commission to plan and implement reorganization and consolidation of Federal agencies for water resources on the basis of watersheds.***

Budget proposals by both major political parties imply the strong likelihood of dramatic reductions in funding for major water-resource agencies after the year 2000. During the late 1990s, most of the major agency players have suggested that one agency or another has as its mission the management of the nation's water resources. It is clear that the fragmented bureaucracy for rivers cannot continue indefinitely, and that consolidation of river managers into fewer agencies will be a budgetary necessity. This reorganization should proceed along the lines of watersheds and river basins. To reduce disruptions among skilled managers and to ensure the flow of monitoring data is uninterrupted, such consolidation should started slowly now rather than be implemented later as a crash program. The consolidation of management agencies will improve the management of the physically segmented river systems, and improve communication among competing interests for limited physical resources. At the very least, an improved overall structure combining the ACE, NRCS, and BR should be considered. The Water Resources Division of the GS,

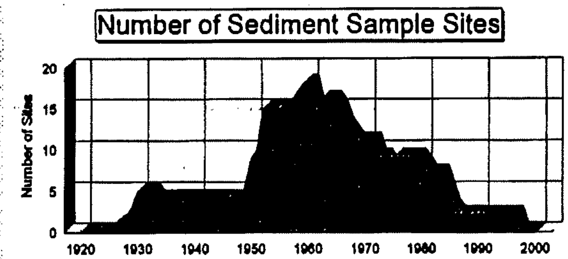


Figure 4. History of the number of sediment sampling sites in the Colorado River Basin, showing the decline in the availability of sediment data since about 1960 (data from 1).

the FWS, and certain components of the EPA must be accommodated as well. Some nations have accomplished this process by establishing river authorities, defined on the basis of the physical system rather than by agency topic. So many options and interest groups are part of this issue, that a general commission is necessary to sort to the possibilities and recommend the most likely structure for promoting sustainability in an era of reduced Federal budgets.

ISSUE: Watershed and political boundaries do not match.

In those few cases where Federal management efforts are defined by the geographic boundaries of watersheds, the boundaries are not truly representative of system operations. In the cases of the Colorado River Storage Project, the Upper Missouri Basin Commission, and the Columbia River Commission, for examples, the strict physical boundaries of the watershed define the area of interest, yet these basins export electrical energy and in either import or export water beyond their boundaries. They serve recreational users, migratory game and non-game species, and non-use values that do not respect physical boundaries.

- ***RECOMMENDATION: Establish flexible federalism for watershed management.***

Strong currents exist in the present political climate to move primary decision-making away from the Federal government to State and Local governments. This trend affects watershed management in the form of emerging watershed councils, consortia of Local, Tribal, State, and Federal agencies organized according to drainage-basin boundaries. The trend should be encouraged and formalized as a National objective as an effective way to partition the administrative process. Representatives to local watershed councils should have considerable authority to negotiate solutions to watershed management problems. The Federal interest should not be eliminated, however, because it is only the Federal government that truly represents over-arching National interests. This broad perspective is especially important when dealing with the physical resources of watersheds, wherein decisions may entail local costs but National benefits. Watershed councils bring into focus the decision-making process by organizing the process geographically to match extent and scale of the natural system being managed. Watershed councils may also deal with the various human controls of the system, including landuse. The USA is unlikely to impose general land use controls through watershed councils, but the Federal government should strive to insure that land users are responsible as well for off-property impacts of their activities.

ISSUE: The physical basis of the western aquatic ecosystem has not received enough attention.

Federal oversight and State actions with respect to the Clean Water Act have heretofore focused almost exclusively on chemical and biological integrity of the Nation's waters. Physical integrity, although part of the Act, has largely been ignored.

- ***RECOMMENDATION: Increase emphasis on the physical Integrity component of the Clean Water Act.***

With Federal guidelines, States should develop definitions of physical integrity appropriate to conditions in their particular regions, with attention to geographic variation in watershed and river processes related to regional hydroclimates, geologic conditions, and terrain configurations. Regulatory approaches may vary from state to state to reflect these variations in processes and forms. The Water Science and Technology Board of the NAS should advise policy makers on scientific aspects of the issue. Successful watershed and river restoration efforts should be conducted in light of efforts to establish and maintain sustainable physical integrity as a foundation for biological and chemical restoration.

ISSUE: Role of hydropower.

The hydropower generated in western watersheds dominates many decision-making processes to the exclusion of other values and objectives. This situation comes about because the infrastructure was in part designed for this purpose, revenues from electrical power reduce the debt on structures, and the power is inexpensive for a group of historically defined users. New social values, especially from a larger Regional or National perspective, challenge primacy for hydroelectricity.

- ***RECOMMENDATION: Redefine the role of hydropower in dam management.***

Hydropower should remain as a principal component of dam operations and management for western rivers, but it should not occupy primacy in the hierarchy of objectives. Wildlife protection, recreational needs, and non-use values of landscape protection should receive increased management consideration in association with water management and hydropower generation. Hydropower generation should not be privatized because proceeds from power sales support all the objectives of dam management (including water resource-management). Relicensing of private structures by the FERC should take into account not only power generation but also maintenance and restoration of the physical integrity of the rivers in question. Removal of some antiquated structures may be in order, such as is occurring on the Elwha River in western WA.

ISSUE: River segmentation.

Dams divide western rivers into segments that do not behave consistently from one place to another, and physical processes do not demonstrate equilibrium among water, sediment, energy, and landforms. Rivers downstream from dams have highly unnatural hydrologic regimes that preclude effective biological restoration because they lack the required physical environments necessary for such restoration.

- ***RECOMMENDATION: Promote restoration of rivers through altered dam operations.***

On most intermediate and large rivers, physical processes and forms that are the foundation of the aquatic system are in large part the reflections of the impacts of dams. Restoration and maintenance of these rivers as required by the Clean Water and other acts depends on minimizing the effects of the dams through altered rules of operation. Water releases from large dams should be scheduled to be as natural as possible, with occasional large releases to mimic events that are smaller than natural floods but far more realistic than constant low-level releases. Adjustments in floodplain management may be needed to accommodate these flood releases. Seasonal fluctuations in releases may also improve wildlife and recreational management downstream from the structures. Lessons from research at Glen Canyon Dam on the Colorado River, Trinity and Lewiston dams on the Trinity River, and the Aspinall Unit on the Gunnison River should be expanded and applied generally on western rivers to promote restoration of their physical components. The adjustments in operating rules for enhancing physical components of the environmental system will result in some lost revenues or costs to power and water users in western states. Since these users benefit most directly from the structures, it is appropriate that they bear the costs.

ISSUE: The Wild and Scenic Rivers System is incomplete.

Many river segments in western states are prime candidates for inclusion in the Wild and Scenic Rivers System, especially in under-represented environments of the Southwest and the Great Plains. A sustainable management effort of the entire western aquatic ecosystem depends on accurate recognition of the nature of the river resources, including those streams that have wild, scenic, or recreational value, especially in light of changing American cultural preferences which place increasing emphasis on these conditions.

• ***RECOMMENDATION: Expand the Wild and Scenic River System.***

National recognition of river segments with natural or recreational potential is incomplete.

Many western river segments, especially in the dryland and Plains zones, have viable candidates for recognition and management as wild, scenic, or recreational streams but have not been included. The designation of these streams to include representatives in the system of a variety of physical and biological types is not likely to foreclose major water resource development projects since the era of construction for large dams is past. Designation may force a balanced consideration of minor projects that, over the long term with cumulative effects, might reduce opportunities for a sustainable system.

ISSUE: Sediment quality.

Although we have a modest understanding of the amounts and processes for contaminants such as herbicides, pesticides, and heavy metals in water, we have little understanding and virtually no standards for the other primary physical component of western aquatic systems: the sediment. Sediment carries more of the contaminants than the water, and although sediment-bound contaminants are not biologically active in some cases, changing conditions depending on the site of deposition with subsequent bioamplification in living organisms poses a hazard.

• ***RECOMMENDATION: Establish sediment quality standards.***

National standards for air and water quality should be extend to sediment, because fluvial sediment is the basic substrate for ecosystems. For many substances, contaminants adhere to sediments in greater quantities than are dissolved in water, so that monitoring of the watersheds and rivers for the protection of human health and ecosystem vitality requires consideration of sediments. Rather than pursue expensive research efforts, Federal agencies should adopt pre-existing standards developed by other countries for common contaminants such as herbicides, pesticides, heavy metals, and radionuclides.

ISSUE: Data collection and information management.

Any Federal effort directed toward sustainable physical watershed resources will need to be in the framework of adaptive management. In this approach, management goals are periodically changed in light of new information about the system. A successful adaptive management program for sustainable physical systems will require that monitoring data be collected in new, less expensive ways, and that the resulting information be collated in a central, accessible location with institutional stability rather than stored in a variety of formats in disconnected agencies.

• ***RECOMMENDATION: Develop new methods for watershed and river monitoring.***

The GS, EPA, and NSF should jointly undertake a program to foster development of new measurement techniques for the physical characteristics of aquatic systems. Automated, simple measurement approaches are needed for water and especially sediment in such systems. The resulting data, along with other information concerning chemical quality, landforms, and biosystems should be stored along with locational data in a geographic information system format administered by the GS's National Spatial Data Infrastructure, which is already established.

Conclusions

Through the past century and a half, western watersheds and rivers have undergone vast changes in their physical systems, partly in response to hydroclimatic adjustments but mostly as a result of human activities. These changes are much greater and more pervasive than any changes envisioned to result from Global climatic changes. Adjustments in magnitude, frequency, and duration of streamflows from highland watersheds have altered the distribution of water, sediment, energy, and landforms that are the basis of western aquatic ecosystems. In the late twentieth century we are left with a partly artificial and partly natural system that is segmented and divided by large dams whose operation controls the physical processes in rivers downstream from the structures. The western fluvial system is not now natural, and may never be natural again. To achieve a reasonably sustainable system, the Federal government must reduce the fragmentation inherent in its management structure for these resources, and adopt a policy of flexible federalism wherein lines of authority and decision making are drawn coincidentally with the physical reality of watersheds and river systems. Although they are radically altered, the physical components of western watersheds and rivers can still contribute to the overriding goals of Federal water resource management: economic vitality for the present and environmental preservation for the future.

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CHAPTER III: SUSTAINABILITY OF WESTERN RIPARIAN ECOSYSTEMS[1]

BY

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Introduction (1-19)

Although relatively few and far between, rivers flow through the mountain and valley landscapes of the western USA. Streamside, or riparian, ecosystems occupy the dynamic zone between the semiarid uplands and fully aquatic environments. Flowing streams deliver water, soil, and nutrients from upland watersheds to the riparian zone, where they are used and stored. This resource abundance makes riparian ecosystems more productive and than any other in the West.

Riparian zones in the arid and semiarid western states are distinct features of landscape, presenting a lively contrast to their surroundings. In this region, streambanks are practically the only natural environments moist enough to allow survival of broadleaved, deciduous trees. And although they occupy relatively narrow bands of territory immediately adjacent to watercourses, riparian ecosystems are now understood to also be consistently the most diverse, regional biological communities.

The same features that appeal to plants and animals also attract recreationists, farmers, ranchers, and a variety of other human users. Riparian ecosystems have helped to sustain human populations for thousands of years, providing sources of water, building materials, forage for domestic animals, and fertile agricultural land. But riparian ecosystems are vulnerable to direct misuse and overuse, and to offsite management practices that alter their natural dynamics and rob them of critical resources. Today, western riparian ecosystems continue to be impacted, often unnecessarily, by seemingly insatiable economic demands and sometimes irrational natural-resource management practices.

Among the most serious human threats to riparian ecosystems in the West are:

- excessive impoundment and diversion of surface water;
- over-pumping of groundwater from riverine aquifers;
- poor agricultural land management;
- unnecessary or unsupervised livestock grazing;
- introductions of non-native species;
- unnatural fire recurrence and intensity;
- needlessly wasteful mining practices;
- hopeless structural flood-control measures;
- poorly planned and regulated road construction and urban development;
- highly concentrated, inappropriate recreational activities; and
- collective degradation of upland watersheds.

Individual threats are, necessarily, more or less important at specific locations; but local, synergistic interactions can cause catastrophic degradation of riparian ecosystems.

The following sections briefly detail the important functional aspects of riparian ecosystems and the physical and biological forces that shape and threaten this important ecological resource. We conclude with an assessment of the prognosis for western riparian ecosystems in the face of ongoing resource-extraction practices. We stress the importance of sustainable development through improved management techniques, and present some recommendations for legislatively addressing riparian management issues.

Riparian Ecosystem Processes and Functions (20-31)

Functions of riparian ecosystems vary with factors including vegetation structure, composition, and abundance; ecological diversity; and landscape position. The riparian zone essentially encompasses the whole floodplain of a river, where river water supplements that available from local precipitation. The abundant vegetation on stream banks and adjacent floodplain terraces reduces soil erosion rates (Box 1). Riparian vegetation physically stabilizes sediments that compose the floodplain, thus preventing excessive soil erosion and deterioration of the whole riverine system. By trapping

[1] With some minor exceptions, references for this paper are not cited in text. Rather, they are provided in blocks corresponding to the major sections: General References, 1-19; Riparian Ecosystem Functions, 20-31; Human Impacts, 31-60; Water and Dam Management, 32-45 and Biological Alterations, 54-60.

(Box 1) Sediment erosion from streambanks, contrasted with erosion of upland sediments, constitutes a large portion of total watershed sediment loss. Estimates range from 26% for the whole USA (31) to 50% for large western watersheds (27).

sediment transported during floods, riparian vegetation reduces downstream sediment loads. Dense stands of riparian vegetation in the floodplain also reduce downstream flood erosion damage, by causing the river to spread while slowing its velocity. Slowing of water velocity also enhances groundwater recharge. Riparian vegetation tends to help prevent the river from downcutting or cutting a straight path, thus promoting the meandering nature of channels, increasing groundwater recharge, and maintaining an elevated water table.

Riparian ecosystems also improve water quality by filtering sediment, nutrients, and pollutants transported by floods. Riparian zones function as the transition zone or ecotone between the aquatic system of the river and uplands. They act as a buffer, "filtering out" materials washing into watercourses (Box 2). The width and vegetation density of the riparian zone reduces passage of soil and sediment lost from eroding, poorly-managed upland areas, and can help immobilize fertilizers, pesticides, and other natural, applied, or spilled chemicals and nutrients that may be present. The widths of potential riparian zones are naturally controlled by factors such as watershed characteristics, valley topography, and stream flow. A narrow mountain canyon produces only a narrow riparian zone, while a broad floodplain on the Plains or in lowland valleys potentially can support an extensive riparian forest. The wider the riparian zone, the greater potential it has to function as such a filter. Fortunately, the most concentrated pollutant-generating conditions often occur where the potential riparian zone is widest.

(Box 2) In an undisturbed headwaters watershed in the Sierra Nevada, CA, riparian and wetland plants contributed to the removal of 99% of the incoming nitrate-nitrogen, a potentially harmful nutrient (26).

Riparian systems have many other important ecological functions. Although they may occupy a relatively narrow band of territory, riparian ecosystems are vital to maintaining the biodiversity of the more extensive, adjoining uplands (Box 3). More than 75% of the animal species in arid regions need riparian habitats for some stage of their life cycles. Riparian ecosystems are often the sole available habitat for amphibians and invertebrates that require moist conditions. Structurally complex riparian communities provide many different habitats and support a diverse array of animal species. Different groups of animals occupy the different "layers" of vegetation, and this multi-story arrangement is often present nowhere else in arid landscapes. Canopies of plants growing on stream banks provide shade, cooling stream water, while roots stabilize and create overhanging banks, providing habitat for fishes and other aquatic organisms.

Recreational use is growing in riparian areas. People are drawn to water, all the more so where it is uncommon. Cool, shady environments along flowing streams invite campers and picnickers where summer conditions might otherwise discourage them. Birders, nature study enthusiasts, hunters and anglers all know the value of riparian areas, and repeatedly visit particular favorites. Recreationists are drawn farther and farther into wilderness areas in search of uncrowded, untrampled riparian groves— often like the places their towns and cities were first sited.

(Box 3) Approximately 47% of birds that breed in the Southwest are restricted to riparian vegetation (21).

Controlling Factors

Many natural factors control the condition of western riparian areas. In this section, we focus our attention on two factors of paramount importance in arid and semi-arid western environments.

Water Supply

The primary reason western riparian ecosystems exist is the presence of an unrestricted supply of water. Most riparian plants are wetland species that cannot survive on local rainfall, requiring a supplemental supply of river water or shallow groundwater. The extent, density, vigor, and species of riparian vegetation present depend on the volume and timing of flows within the system. Watershed characteristics, precipitation, and other climatic factors influence the volume and timing of flows in a stream. Rapid spring snowmelt or intense thunderstorms can produce periodic flooding, while normal "baseflow" conditions result from milder rains and the gradual release of groundwater and snowmelt. Periodic floods, such as spring runoff, influence establishment of riparian plant seedlings. High flows scour portions of the floodplain and redeposit sediments, allowing tree seedlings to germinate and grow on bare sandbars without competition from established plants. Most native riparian plant species disperse seeds as annual high flows subside. In the arid Southwest, cottonwoods and willows release seeds in March and April as winter floods decline. In MT, cottonwoods disperse seed after spring floods from snowmelt in late May and June. The gradually declining flows keep flood-deposited soils moist as seedlings put down roots. As plants mature, they continue to depend on the shallow river aquifer or upland runoff collected in the floodplain.

Landscape Characteristics

The vegetation and climate of a river's watershed greatly influences volume and timing of stream flows. Watersheds with little vegetation cover, such as those of the desert Southwest, release water almost immediately after a storm. Forested watersheds enhance groundwater recharge, resulting in slower releases. Watersheds with many evergreen plants such as chaparral shrublands in CA and AZ or coniferous forests of western mountains will use water throughout the year, reducing the total amount of runoff to stream channels. Watersheds with winter deciduous or dormant plants like aspen or grasses often release more water to streams in winter than summer unless the water is stored as snow. Topography and soil cover also significantly affect runoff. Steep terrain, exposed bedrock or thin, stony soils produce greater streamflow volumes more quickly than gentle slopes and deep organic soils.

Human Impacts (32-60)

People influence riparian ecosystems by using and managing land and water and by introducing or removing plant and animal species. Natural resource management, most notably as relating to resource-extraction industries, has both direct and indirect effects on the abundance, structure, composition, productivity, and functional integrity of riparian ecosystems.

Changes in Water Availability

(Box 4) The Colorado River Basin is one of the most regulated, with with more than 20 major dams controlling the flows of the mainstem Colorado River and its major tributaries.

Population growth in the West depended primarily on the easy availability of water. From the 100th meridian to the crests of the Sierras and Cascades, western USA is arid to semi-arid. Droughts are a fact of life and climate, and the ability of ranchers, farmers, and communities to survive depends on the control and delivery of water. Consequently, very few western rivers remain free-flowing (Box 4). Rivers have been managed regionally to produce water for irrigation, generate hydroelectric power, and more locally for flood control. Large dams were constructed on many of the West's large rivers, and the resulting impoundments cover a large part of their original channels and floodplains.

Water and Dam Management. (32-45). Four examples are the Colorado, Missouri, Snake and Columbia rivers. Without the multiple, major dams that impound these and many of their tributaries, spring floods would scour the channels, deposit sediment, and develop riparian vegetation along the high-water zone, while late summer and winter flows would be relatively small. As presently practiced, agriculture requires water during the traditional summer growing season typical of more moderate climates. Water held behind dams is released in large quantities only during the summer (dry) season when crops require supplemental water. These releases do not coincide with normal high-flow periods for the river or the region, so riparian vegetation that depends on high spring flows will have insufficient flows for germination, or seedlings germinating at lower flows will be scoured away by higher, managed, summer releases. As a result, riparian ecosystems along these major rivers have largely collapsed, and remnants occur only where local conditions favor their persistence.

In extreme cases, such as the Salt and Verde rivers in AZ, no water is released downstream unless upstream impoundments have insufficient capacity for containing winter or spring floods. Consequently, the river, riparian zone, and most of the riparian ecosystem below the final irrigation diversion is simply gone. There remains a fragmentary semblance of a riparian ecosystem only at disconnected sites where municipal storm-water runoff, irrigation return flows, or treated municipal effluent is released into the channel.

Other dams are operated on a "flow of the river" policy, that is, the amount of water flowing into the impoundment is released at the same time from the dam, especially during high flows. The impoundment is used to assure downstream water during dry periods and to control major floods if it has the capacity. Dams on the upper Missouri are operated in this fashion. Unfortunately, although timing and amount of water may be sufficient for recruitment and maintenance of riparian vegetation, the river carries little sediment below the dam, except for that entering from tributaries. Because sediment deposits are so

(Box 5) Cottonwood and mesquite forests along the Santa Cruz River near Tucson, AZ, have given way to a dry, barren riverbed, as a result of municipal and agricultural groundwater use (33).

important for recruitment, riparian vegetation is greatly reduced or lost.

Groundwater Removal. Groundwater withdrawal also affects stream flow throughout much of the West. In most cases, surface flow is hydraulically connected to the water table. When wells for irrigation, mining, or municipal use are drilled adjacent to the river, or even away from the river in the aquifer recharge zone, a "cone of groundwater depression" caused by withdrawal will develop. Either way, the result often is a drop in the water table and reduced stream flow. This reduces the vigor of riparian vegetation, and ultimately can cause its death and prevent re-establishment (Box 5). Examples of this effect are becoming increasingly common in the Southwest where limited rainfall cannot replenish the groundwater extraction "overdraft."

Groundwater pumping for agriculture, urban (metropolitan and industrial) use, and mining is common throughout the region. In some areas recharge from surrounding mountains can maintain a sufficiently high water table to prevent riparian losses. However, often this is not the case. For example, in some NV valleys where groundwater is pumped to support agriculture, the overdraft has depleted aquifers that feed desert springs and dried up their small outflow streams. Regional groundwater pumping similarly threatens springs that support many rare and endemic species at Ash Meadows NWR, west of Las Vegas.

Landscape Use and Change

Riparian ecosystem condition reflects the cumulative effects of all activities that influence hydrological conditions in watersheds. Watersheds throughout much of the West are mountainous, and landscape modifications on steep terrain may quickly affect downslope and downstream ecosystems. Multiple resource uses on mountains and in valleys have modified both the quantity and quality of water entering rivers from these areas. Sometimes the results of landuse can be subtle, while in other cases downstream impacts on riparian ecosystems are dramatic.

Timber Harvest. Timber harvest in the west is most commonly achieved through clear-cutting of forests, especially in the Cascade, Olympic, Coastal Range, and Rocky mountains. Rain falling on these large, cleared areas causes increased soil erosion and results in more rapid runoff. Floodflows often become larger and carry too much sediment. Percolation of rainfall and snowmelt into the ground is reduced, and with them the baseflows that sustain riparian vegetation during dry seasons.

The recent practice of leaving a buffer zone between clearcuts and streams have reduced some of the negative impacts of watershed forest cutting. Buffer strips help to reduce sedimentation rates, and provide for continued ecological interactions between streams and riparian vegetation that maintains fish habitat and aquatic food chains. However, buffer zones are inadequate to prevent all adverse impacts of clear cutting, and are often too narrow to accomplish their intended effects.

Riparian forests also are directly affected by timber cutting. Cottonwood forests along rivers of the Plains, for example, are cut for wood products. This direct loss of habitat diminishes the ability of the riparian ecosystem to sustain wildlife and carry out the other valuable ecological functions discussed before.

Grazing. Riparian areas offer water, shade, and food for domestic livestock. Cattle and sheep congregate in riparian areas, particularly during hot or dry periods when upland forage production is low and water is locally unavailable. Springtime grazing in riparian areas disrupts the reproductive cycle of riparian trees such as cottonwoods, whose broadleaved seedlings and saplings are as palatable to cattle as grasses and other herbaceous cover. Domestic livestock concentrated in bottomlands for extended periods destroy riparian ground cover, destabilize stream banks, and thus increase sediment loads to streams. Uncomplicated changes in grazing management can greatly reduce the negative impacts of domestic livestock on riparian areas. Individual ranchers have enthusiastically endorsed and adopted new techniques, producing significant local improvement in riparian ecosystem conditions. But the industry as a whole appears resistant to improvement and appropriate riparian grazing management has not been widely implemented.

Where managed for high visibility or high density, native wildlife populations also have locally damaged riparian ecosystems (Box 6). In some National parks and urban greenbelts, deer, elk and even bison populations have expanded well beyond the long-term carrying capacity of the "protected" area. Lacking natural (or human) predators, and unable to emigrate seasonally or permanently, these animals cause the same problems as concentrated domestic livestock. Even in relatively unconfined environments, wildlife managed to maximize hunter satisfaction can decimate riparian vegetation. The Rocky Mountain elk that were imported to northern AZ are a hunter's dream, but a riparian manager's nightmare.

(Box 6) The elk herd, along with an expanding bison population, has over-utilized woody riparian vegetation in northern Yellowstone National Park. Interaction of domestic livestock and wildlife, such as cattle and elk in the mountains of the Southwest, produce a similar decline in riparian vegetation and habitat quality.

Agriculture. Irrigated agriculture is traditionally the most insatiably thirsty activity in the West. Stream diversion for irrigation may reduce surface flows to a level insufficient to maintain riparian vegetation, while groundwater pumping lowers local and regional water tables and reduces stream flow, either of which can eliminate or weaken riparian vegetation.

Many broad alluvial valleys historically had rich soils and shallow water tables, and so were extensively cleared for agriculture. Clearing of riparian vegetation to make way for fields causes direct loss of wildlife habitat and water and sediment-buffering ability. Some uneconomic farmlands now lay fallow and are being restored to riparian vegetation. Remaining agricultural activity on floodplain lands is sustained by irrigation and fertilizer, to compensate for losses in natural fertility and regionally low precipitation.

Irrigation runoff ("return flows") from farms typically carry salts and other pollutants into streams, adversely affecting aquatic and riparian ecosystems. Maintenance of a riparian buffer zone between agricultural fields and rivers can greatly reduce the impacts on the riverine system, especially where natural flooding periodically cleanses the riparian ecosystem itself.

Mining. Hardrock mining is common in mountainous parts of the West. Softrock mining, especially strip-mining for coal, occurs more commonly in grasslands and deserts of MT, WY and AZ. Extraction of sand and gravel aggregate materials from floodplains and remnants of Pleistocene river terraces and outwash plains is another common form of mining and is closely tied to rapidly expanding human developments.

Hardrock operations, such as open-pit copper mining, generally disrupt the landscape surface while appropriating natural valleys for waste or leach pads and tailings ponds. Such operations can consume all available water, usually obtained through extensive groundwater pumping. Valley filling locally destroys riparian ecosystems by burying the entire area with overburden rubble or exhausted tailings. Groundwater pumping lowers the water tables of some nearby, unburied streams and springs. Mines also may intercept the deep water table, disrupting regional aquifers and reducing stream and spring flows over a large area. In our more arid states (e.g., AZ, NV and UT) there are already major riparian or riverine ecosystem impacts from hardrock mining. The potential for even greater damage looms large.

Mining also produces chemical contaminants that find their way into streams. These include naturally occurring heavy metals such as copper, lead, and arsenic, direct outputs of mining; or compounds used for ore leaching such as cyanide and sulfuric acid. Acid outflow from tailings lowers stream pH (i.e., produces high acidity), kills plants and animals in affected stream reaches, and prevents re-establishment of the aquatic biota. Extremely acid leachate from abandoned mine tailings, as documented in the San Juan Mountains in CO, have produced dead, sterile rivers.

Strip-mining for coal, when carried out near rivers, can contaminate them and cause channel alterations. Although most coal transport is accomplished via truck or train, some is transported in slurry pipelines which require large amounts of water, in most cases from deep aquifers. In some cases, withdrawal of even deep water may reduce surface flows or dry up shallow wells.

Sand and gravel mining destroys the riparian vegetation that is removed during excavation, but also indirectly jeopardizes the rest of the local riparian ecosystem. Whether undertaken within a river channel or on the adjacent floodplain, aggregate removal can lower water tables and reduce or eliminate surface flows (Box 7). Some gravel pits must be continually pumped to provide access to sand and gravel deposits. Nearby channels dry up or migrate toward these low-lying basins. The lowered water table may be beyond the reach of riparian plant roots, and trees growing along dried-up or abandoned channels are likewise left without sufficient water. Especially near fast-growing urban areas, riparian and river ecosystems are left cratered and fragmented by this widespread but little-regarded activity.

(Box 7) A rapid drop of over 2.0 meters in the alluvial groundwater table resulted from an inchannel sand-mining operation in Colorado, leading to the deaths of 80% of nearby cottonwood trees.

Urbanization and Road Development. Western USA is experiencing massive population growth, primarily in urban areas including metropolitan Las Vegas, Los Angeles, Phoenix, Denver, Salt Lake City, Portland, and Seattle, as well as in smaller cities such as Bend, OR; Bozeman, MT; and Prescott, AZ. Expanding population centers directly impact streamside lands that once supported riparian ecosystems, and continually increase their demands on a decidedly finite water supply. As a result, many (perhaps most) urban riparian ecosystems are already gone, and survival of many remaining fragments is in doubt.

Many western towns were founded along rivers because of the ready water source and (along major waterways) the transportation potential. Even where stream navigation is impractical, highways and railroads follow river valleys, often the gentlest available grades. Cities expanded along these major transportation routes, often directly within floodplains. Some riverfront property is valued for aesthetic reasons, some for commercial and industrial convenience; but riverfront development directly competes with riparian ecosystems for the critical strip of bottomland. Belatedly realizing their loss, some towns have attempted to preserve or even restore riparian areas. But ever-increasing land values bring development pressures and elimination of natural biological communities in favor of up-market concrete ones. Runoff from these hardened urban watersheds is immediate and intense, sometimes actually lowering nearby riparian water tables as it causes rapid erosion and downcutting in stream channels.

Stream water or groundwater used by cities often is disposed of in the form of treated sewage effluent. In extremely arid regions where rivers have been totally or largely dewatered, returning effluent to a depleted channel can reestablish and maintain riparian vegetation. The potential for using effluent for riparian restoration and maintenance is great throughout the West. Though it may not meet some current clean-water standards for a short distance downstream, biological processes in a recovered, effluent-dependent riverine/riparian ecosystem will ultimately improve downstream water quality sufficiently to meet necessary standards.

When valley bottom and riverside roadways were small and less traveled, impacts on rivers and associated riparian areas were proportionately minor, but as highways expanded from small tracks to multilane freeways the impacts increased. Widening existing, traditionally located highways has sometimes required redirecting rivers and constricting stream flows. Established riparian ecosystems were destroyed while re-engineered channels are too steep-sided or fast-flowing to allow new ones to become established. Minor roads constructed to facilitate rapid mineral and timber resource extraction are rarely constructed for long-term stability, increasing erosion potential and reducing in riparian vegetation cover and stream water quality.

Recreation. The popularity of riparian recreation sites leaves them vulnerable to overuse and misuse. Motorized recreation has major impacts in many riparian resources. When stream flows are low, channels may become thoroughfares for four-wheel drive and all-terrain vehicles, to the detriment of riparian vegetation and soils. Every human presence leaves its mark, but riparian ecosystems are resilient and rebound easily if use is limited. Continuous or repeated, intense recreation, like uncontrolled or constant domestic livestock grazing, causes the most ruinous impacts.

Biological Alterations (54-60)

People bring plants and animals they are familiar with in old-home settings to their new surroundings. Plants may be deliberately imported as ornamentals, food, or fiber sources, or for some other functional purpose. Many are also accidentally introduced. Intensive or poorly timed livestock grazing, and dam-induced changes in flood timing and magnitude often favor the survival of introduced species and allows thriving exotics to displace native species.

One introduced riparian species that continues to be recommended as an ornamental and distributed by commercial plant nurseries is Russian-olive, which successfully competes with native riparian species, especially along more northern rivers. As long as it continues to be planted in urban and rural settings, a seed source will always be available and it will be difficult to control or remove from western riparian ecosystems.

Tamarisk, or saltcedar, was introduced from the Near East to the American Southwest as an ornamental shrub more than 100 years ago. It was highly touted as a streambank stabilizer and an efficient, drought-tolerant windbreak during the Dustbowl Era. But now it has overrun floodplains from TX to CA and north to WY and eastern MT, occupying over 500,000 ha of riparian habitat. Near Yuma, AZ it occupies up to 90% of the area originally dominated by cottonwood-willow riparian forests.

Saltcedar is very difficult to remove

from human-impacted riparian areas. It produces incredible numbers of tiny, wind-dispersed seeds throughout the growing season. It can repeatedly resprout after fire, cutting, or browsing. And it tenaciously survives in very wet, very dry, or very salty soils. In other words, saltcedar has the fortuitous ability to take advantage of conditions now prevalent on western streams and rivers: overgrazing, salty irrigation runoff, and dams preventing normal spring floods. It can now out-compete most native riparian trees and shrubs throughout its adopted range, and this domination produces a simplified community of weedy exotic plants, lacking the multi-story structure and high biological diversity of native riparian woodlands. Saltcedar ecosystems are also particularly flammable, a condition that few native riparian species tolerate. Only along free-flowing rivers, where grazing and agriculture are eliminated or managed at sustainable levels, are cottonwood and willow likely to reclaim lost territory.

Issues and Recommendations

Under the existing legal, regulatory, and land-management paradigm of the West, destruction and alteration of western riparian areas can only continue. As Americans abandon older cities and suburbs in favor of mythical wide-open spaces, population increases and unsustainable natural-resource exploitation intensify. More and more surface- and groundwater will be dedicated to human desires. Timbering and mining will spread to increasingly marginal sites and affect greater and greater areas to keep up with spiraling material demands. Increasingly mechanized, leisure-time activities will continue to conflict with calls for maintaining vestiges of natural ecosystems and natural space. Outdated tax incentives and subsidies maintain otherwise uneconomical open-range cattle grazing. But there are now important opportunities to alter land and water management practices harmful to riparian ecosystems. Many of these issues can be addressed by instituting thoughtful policies, planning and management that recognize the Nationally popular goal of conserving natural ecosystems and their processes.

ISSUE: Dam Construction and Operation.

Construction and operation of dams has severely modified both up- and downstream hydrology and landforms, disrupting natural conditions that influence abundance, structure, and function of native western riparian ecosystems. Dams have been constructed on most of the major Western rivers. Some were ill-advised pork-barrel projects without practical justification; others have outlived their usefulness and can safely be removed. Proper planning for removal of dams must address factors such as sediment accumulation behind the dam and effects of rapidly restoring a free-flowing river to long-established, altered riverine systems below.

• ***RECOMMENDATION: Require review of utility of existing dams.***

Agencies that manage water and dam operations, such as the BR and ACE, should review the needs for existing dams, and give significant weight to ecological considerations during scheduled planning reviews. They should publicly weigh the options of dam removal, alteration of dam operations, and continuation of the status quo in light of how such actions will influence up- and downstream riparian ecosystems. Demolition of a major public works project may seem politically infeasible at first glance, but demonstrates a commitment to curing well-intended (or otherwise) mistakes of the past.

ISSUE: Change dam operations-water release patterns.

Operations of dams will change in the future. The successful, controlled Grand Canyon flood in March-April, 1996, represents one promising dam-management approach, attempting to simulate natural flow regimes to "repair" some downstream ecological changes caused by damming. Controlled releases can mimic the effects of natural flooding events, and also mimic normal, seasonal river-flow dynamics. Increasing (or decreasing) baseflow releases at appropriate times can help maintain riparian vegetation established under artificial flows.

• ***RECOMMENDATION: Establish a policy for dam operations that requires consideration of below-dam ecosystems.***

Agencies that operate dams need encouragement to "naturalize" downstream flows. Water should be released in a fashion that mimics the seasonal amount and timing of natural flows, to conserve, restore and/or enhance downstream ecosystems. Passage of legislation similar to the Grand Canyon Protection Act for other dams and rivers will accelerate this process. FERC relicensing reviews should also encourage maintenance of native downstream riparian ecosystems.

ISSUE: Sediment Management.

Dams disrupt normal patterns of sediment transport and deposition. Sediment rebuilds floodplains, providing sites and a nutrient source for most riverine ecosystems. Most western dams are slowly silting in as rivers drop their sediment loads into reservoirs, and "sediment hungry" water is released downstream. The Grand Canyon experimental flood mobilized below-dam sediments that originated from tributaries and side canyons; however, larger amounts of reservoir sediment may have to be moved downstream as well, as secondary sources are depleted.

- ***RECOMMENDATION: Add sediment bypass systems to existing dams.***

Movement of sediment through pipelines and restoration of sediment to below-dam river reaches should be studied and planned for rivers of high downstream ecological importance. Sediment release should be synchronized with flood-mimicking discharges from the dam, or anticipated seasonal floodflows from tributaries, to approximate the naturally occurring patterns of water and sediment releases to which native riparian species are adapted.

ISSUE: Reservoir Fluctuations.

Impoundments behind many western dams often have shoreline elevations that fluctuate wildly as flood flows are captured or water is released for hydropower and downstream irrigation. Stabilizing reservoir elevations, or timing drawdowns to coincide with biological needs of native vegetation, will lead to establishment of vegetation that can partially mitigate for destruction of riparian ecosystems inundated by impoundment. The riparian zone would function as a buffer, filtering inflows from the surrounding uplands and helping maintain lake water quality.

- ***RECOMMENDATION: Require dam-operating plans to conserve, restore, and enhance lake-shore ecosystems.***

Annual operating plans for dams controlled by DOI agencies, approved by the Secretary of the Interior, should consider not only amounts of water withdrawn from a reservoir to satisfy downstream user needs, but also should include ecologically based limits on annual fluctuations in surface elevation, thus maintaining a relatively stable reservoir level and subsequent water support for shoreline riparian vegetation. Similar planning should be also be part of FERC hydropower-dam relicensing procedures.

ISSUE: Groundwater Withdrawal.

As surface waters are over-allocated and overused, there will be an increasing demand for groundwater. Increased energy costs to lift water from lowered water tables will preclude cheap agricultural use of groundwater, but this consumption will be supplanted by municipal and industrial use. Groundwater withdrawal and watertable declines has caused desertification of many aridland floodplains, replacing rare riparian habitats with more common arid shrublands.

- ***RECOMMENDATION: Establish policy to reduce effects of groundwater pumping on streamflow and riparian vegetation.***

Legislation (Federal or State) and administrative rules should continue to be established that limit the groundwater pumping that affects stream flows and riparian areas. All western states need to awaken from the dreamy legal disconnect between surface- and groundwater. Only when surface waters and underground aquifers are properly recognized as an interactive unit will riparian ecosystem survival be considered in the management of groundwater withdrawal.

- **RECOMMENDATION: D*etermine interbasin hydrological connections.***

Hydrogeology of the basins of western USA needs to be better researched and documented. Once we understand connections among western water sources, we will be better able to manage them and prevent destruction of riparian systems. For example, deep-aquifer withdrawal in eastern NV for agricultural and municipal use has been demonstrated to affect desert springs hundreds of kilometers from the pumping location. The GS should be encouraged to make increased mapping of western hydrogeology a priority item in future planning and budgets.

- ***RECOMMENDATION: Recharge groundwater using surface waters.***

Re-create and sustain natural subsurface reservoirs. Authorize and fund GS and/or State water-resource agencies to determine which basins exhibit groundwater decline and riparian loss that is restorable through groundwater recharge using "surplus" surface waters from adjacent basins. Establish policies and procedures by which these transfers would be made. Use unallocated surface water during wet years. Establish policy that encourages storage of surface waters in underground aquifers. This may be a partial solution to future water needs and reduce impacts of water withdrawal on riparian ecosystems.

- ***RECOMMENDATION: Release treated or partially treated sewage effluent directly into stream channels or adjacent aquifers.***

Effluent has become a major source of water for creation and maintenance of flows in arid-land streams. Policy should be established that encourages use of treated effluent to restore river flows and riparian ecosystems, recognizing that it may not meet normal clean-water standards for some distance downstream from release point.

ISSUE: Landuse Modifications.

Many destabilizing changes in watershed landscape characteristics may be reversible. Some components of the landscape have been irretrievably altered, while others can be fully restored or partially rehabilitated through management changes. Guidelines for resource management need to be improved. Resource extraction must not supersede sustainability of natural ecosystems. The issue is not whether, but how best to improve management guidelines to accomplish this vital accommodation of ecological reality.

Forestry. Extraction of renewable resources such as timber may cause major landscape changes, including increased runoff and loss of sediment and nutrients from forest soils. All these changes have damaging consequences for riparian ecosystems in logged-over watersheds. These changes are reversible, given adequate time, and assuming long-term sustainable forest management both during harvest and forest restoration.

- ***RECOMMENDATION: Institute watershed forest management practices that conserve and sustain river and riparian ecosystems.***

Such practices include, but are not limited to: a) widening forest buffers; b) establishing "reference" watersheds in which no cutting is allowed, to serve as ecological 'control' and comparison areas; c) eliminating clearcutting in steep mountainous terrain to reduce erosion, often accelerated by high rainfall periods (such as winter 1996-97). The FS should be given the authority to deny permits for forest cutting if such cutting would be likely to damage watersheds.

Grazing. Riparian ecosystems have tremendous ability for self-repair if natural processes are restored and damaging practices are halted. If livestock is removed from riparian ecosystems, or managed more effectively, riparian ecosystems can recover rapidly. Watershed damages resulting from centuries of poor livestock grazing management practices in the uplands, however, may be irreparable in our lifetimes.

- ***RECOMMENDATION: Institute grazing management practices that conserve and sustain river and riparian ecosystems.***

In some climatic regions and on some stream types, grazing management practices such as reductions of stocking rate, protection from grazing during sensitive seasons, and annual (or longer) rest between grazing, will bring about positive changes to riparian ecosystems. On many desert rivers, however, conservation of native riparian biodiversity can be accomplished only by eliminating all livestock grazing; this notion needs to be incorporated into policies of Federal land managers including FS and BLM. These Federal agencies need the authority to deny grazing leases based on existence of unacceptably damaged riparian conditions, or on susceptibility of an area to ecological damage from grazing. Renewal of grazing releases should be made contingent upon achievement of riparian protection/ enhancement goals.

Mining. Mineral extraction often alters watersheds to the extent that long-term recovery of riparian ecosystems is unimaginable. Mining also uses large amounts of groundwater, often dewatering streams. Development of the proposed Carlota Mine on Pinto Creek and its tributaries near Miami, AZ, is an example of a private project, partially on FS land, that will fill a wooded valley with a leach pad and extract up to 1,200 gallons of water per minute from the local deep aquifer. This pumping will reduce surface and subsurface stream flows in an adjacent, forested riparian area. Only when long-term riparian and other riverine values are given consideration equal to the short-term, boom-and-bust windfall of public-lands mineral extraction, will future mining ventures leave a less distinct bootprint on the landscape.

• ***RECOMMENDATION: Institute mining management practices that conserve and sustain riparian ecosystems.***

This could be accomplished by modifying the 1872 Mining Law so that ecological integrity is given priority status in agency decision making. The 1872 Mining Law ties the hands of Federal land management agencies. They are left with no recourse other than to permit mineral extraction on public lands, or allow the land to be patented, regardless of the predictable negative impacts of mining activities on ecological attributes of the mined lands and surroundings.

Agriculture. Landuse for agriculture will probably not diminish overall; however, many floodplain lands are no longer suitable for agriculture because of salinization. Agricultural use of floodplains results in return of saline irrigation water to streams, enhancing establishment of non-native and halophytic (salt-tolerant) plants in areas once dominated by native or non-halophytic plants. To preserve riparian ecosystems, there is a need for better management of floodplain lands and a significant buffer zone between active agricultural lands and adjacent rivers.

• ***RECOMMENDATION: Establish landuse policy within Federal agencies that requires riparian buffers.***

Developing improved models to determine appropriate and effective buffer widths may assist in better agricultural land planning, reducing the loss and alteration of riparian areas, and improving water quality.

• ***RECOMMENDATION: Increase use of Federal funds (e.g., Land and Water Conservation Funds) for purchase of floodplain lands.***

Purchasing "retired" or marginal floodplain agricultural lands is economically feasible and ecologically desirable. Once purchased, such lands can be transferred or sold to Federal or Private land-management organizations. It may be necessary to actively restore riparian vegetation to fallow fields, but the benefits of healthy riparian ecosystems greatly outweigh the costs.

• ***RECOMMENDATION: In future re-authorization of the Clean Water Act, recognize that riparian ecosystems are integral to "restore and maintain the chemical, physical and biological integrity of our Nation's waters") and thus warrant protection under the Act.***

Riparian ecosystems in the arid and semi-arid lands of the West, although not as 'wet' as wetlands in mesic regions of the East, serve the same function in improving water quality. If protected under the Clean Water Act, riparian ecosystems would have increased ability to reduce the levels of salts, nutrients, and chemical pollutants from the Nation's waters.

Urbanization. Urbanization and road building in the future must respect the integrity of the riverine and riparian systems. Respect for these systems will result in an integration of human and natural communities, where one will benefit and the other will be sustained.

• ***RECOMMENDATION: Limit Federally funded highway construction to areas that do not impact riparian areas.***

Current policies and practices consider immediate monetary costs ahead of ecological integrity. Federal Highway Administration funding guidelines and NEPA documentation policies should be changed to favor the maintenance of intact riparian areas.

• ***RECOMMENDATION: Discourage urban and residential development in floodplains through Federal insurance policy and landuse support systems.***

Development and construction in floodplains should be discouraged by withdrawing FEMA funding eligibility from repeatedly-flooded areas. One-time incentives to rebuild "uphill" should be made available in all cases where 50% or greater individual property damage loss due to floods is documented. Federally subsidized mortgage and small-business loans should be made completely unavailable in floodplain areas.

ISSUE: Biological alteration of ecosystems: introduction of non-native species.

The continued spread of non-native plant species in western riparian ecosystems presages an increase in their influence on riparian ecosystem structure and function. Exotic dominated, altered ecosystems are generally less biologically diverse and aesthetically valuable natural ones. Continued, purposeful, or negligent introduction of invasive non-native species should be curtailed. Land and stream management practices should be established that help eliminate non-native plant species.

• ***RECOMMENDATION: Encourage Federal land-management agencies to classify many of the non-native riparian species as noxious weeds.***

Federal lands managers must be empowered to eliminate invasive exotic species.

• ***RECOMMENDATION: Encourage Federal land and water managers to establish management procedures that will enhance rehabilitation of native riparian plant species.***

Alteration of grazing patterns and reestablishment of natural stream flows will benefit recruitment and growth of native riparian plants and allow them to outcompete non-native species that encroach upon riparian areas because of improper land and watershed management practices.

• ***RECOMMENDATION: Encourage Federal land-management agencies to use only native species when reseeding and revegetating uplands and riparian lands.***

Some plant species introduced into uplands inevitably find their way into riparian areas, where they can cause harmful changes to riparian ecosystems. Throughout watersheds, as well, high cover of non-native plant species can cause harmful changes such as increasing the intensities and spread of fires.

ISSUE: Cumulative Impacts.

Landuse laws and regulations that affect riparian ecosystems are inherently fragmented, and few and far between. The Clean Water Act provides some protection for the Nation's wetlands, but the lion's share of riparian ecosystems in the West are not considered as wetlands under this legislation. (This, despite the fact that they are the main lands that serve to "restore and maintain the chemical, physical and biological integrity of our Nation's waters"). One way to address cumulative impacts to riparian ecosystems is to pass legislation that provides specific protection to threatened ecosystems (of which Western riparian ecosystems surely qualify); or establish a single administrative body that oversees riparian conservation and management. Such efforts are highly improbable.

• ***RECOMMENDATION: An alternative way to conserve native riparian biodiversity and address cumulative impacts is to increase the designation of Riparian National Conservation Areas and manage such areas for their natural ecological values.***

Conservation Area status should be given to representative rivers and riparian ecosystems throughout the West. The San Pedro National Riparian Conservation Area, located in southern AZ, is an example of a riparian ecosystem that has dramatically increased in natural value after receiving this designation, and having landuses such as livestock grazing and gravel mining discontinued. However, protection from land and water uses is not guaranteed by such designation, exemplified by the ongoing threats to the San Pedro River's critically important riparian ecosystem from regional groundwater pumping occurring outside the Conservation Area boundaries.

• ***RECOMMENDATION: Adopt a fourth river class under the Wild and Scenic Rivers Act that recognizes the biologic and ecological value of river corridors.***

Such a class could be designated as "Natural," and would require that the agency managing the river give ecological condition priority when determining allowable uses on the river. Also, Federal agencies should be able to administratively list rivers as Proposed Wild and Scenic, allowing the rivers and riparian corridors to receive protection under the Act until a formal Congressional decision is made.

• ***RECOMMENDATION: Encourage programs that address environmental management issues on a watershed basis, such as the EPA Watershed Protection Initiative.***

Comprehensive and holistic approaches will provide the most effective protection of the functional value of riparian ecosystems, which serve as indicators of the health of our Nation's watersheds.

Conclusions

There is little likelihood that rivers and riparian ecosystems of western USA will ever recover to a pre-Columbian state. However, with a more appropriate legal structure and improved resource management and better urban and rural planning, we may be able to rehabilitate and prevent further destruction of our riverine ecosystems, which are so important to the well-being of the region. Decision making must be based on better awareness of issues and consequences of actions.

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CHAPTER IV: SUSTAINABILITY OF WESTERN WATERSHEDS: NUTRIENTS AND PRODUCTIVITY

BY

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Introduction

The American West is a region of great contrasts in elevation, climate, watershed vegetation, landuse, and water supply. Rivers connect this diverse landscape and exhibit unique character as a result. From multiple beginnings in high mountains or plains, rivers are branched ecosystems that dissect the terrestrial landscape and connect it with the sea, with reservoirs and lakes, or with underground aquifers. Because of intimate connection with the land, the chemistry of rivers reflects the processes of their watersheds, including physical weathering, plant uptake and release of nutrients, soil storage and transformation, distinct riparian (streamside) features, and nutrient retention characteristics of groundwaters.

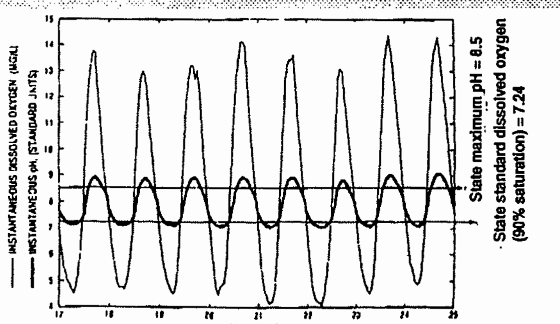
Once water enters the river the process of transformation is by no means finished, for ecosystem processes begun in the terrestrial environment continue along the river's length. Nutrients, the chemical elements required for life, are supplied from the watershed. In rivers, they support aquatic and riparian primary productivity, the creation of new, living, organic material (in this case, algae and trees) via photosynthesis. Processes that remove nutrients from solution (such as plant uptake) collectively reduce the downstream transport of nutrients. Thus, river ecosystems have multiple functions: they are transporting systems, they provide habitat for organisms, they act as water-quality regulators through retention and transformation of materials, and they produce resources that are essential for both humans and wildlife. To achieve sustainable river ecosystems (33, 37), policy must consider the natural balance between the functions of transport and retention, as this balance is important to riverine structure and function.

A river integrates the activities, natural or otherwise, of the watershed it drains. Human landuse practices including agriculture, grazing, forestry, mining, and urbanization occur in upland environments, often far from the river. These activities and likely changes in landuse with continued population growth are, in fact, profoundly connected with river ecosystem health. Landuses simultaneously affect the quality and quantity of materials in transport, i.e., the river's load, and alter the river's ability to process the material delivered to it from the land, i.e., the river's function. Ecologists and hydrologists increasingly recognize that river ecosystems are more than surface water flowing in defined channels; rather, there is an intricate connection among riparian (streamside) zones, floodplains, surface waters, and subsurface water (the hyporheic zone and connected groundwater; 6, 24, 36). Sustainability of function in river's ecosystems depends upon maintaining the relative balance between material retention and transport. This balance is supported by connections among systems.

Except for Coastal Pacific Northwest and high-elevation sites throughout the region, much of western USA is water-limited. Although a relatively small percentage of western lands is dedicated to agriculture, the need to irrigate crops results in exceptionally high water demand to support this landuse. In most western states, agriculture accounts for near 90% of total water consumption. Coupled with the observation that most of the areas of greatest population growth are in the dry Southwest, demand for water relative to supply will continue to grow in the future. This basic supply-demand imbalance has resulted in numerous alterations to the timing and volume of water delivery and its associated solute and sediment load to western rivers. Alteration of the timing and amounts of water and nutrient delivery has clear effects on chemistry and productivity of river ecosystems. For example, increased nitrogen (N) loading from fertilizer application, animal manure, leguminous crops, or air pollution, increasingly stresses riverine ecosystems by overwhelming their capacity to retain and transform the N. In turn, this can affect biotic community structure and function. Severing the connection between surface water and riparian and subsurface systems through channelization, flow regulation, or riparian removal, reduces the capacity of the whole river-corridor ecosystem to effectively handle inputs, resulting in loss of species and sustainability.

Near-full utilization of surface-water resources fosters an increasing reliance on groundwater resources, which lowers water levels of floodplain aquifers, dries riparian zones, and changes flow patterns of perennial streams and springs (in some cases, perennial rivers and springs have dried up). Historically, running waters of the West were characterized by extreme variability of flow, creating

(Box 1) ***The link between primary production and water quality in an effluent-dominated river: pH. by Diane M. McKnight.*** *The South Umpqua River of western OR receives treated sewage effluent from five municipal treatment facilities, which accounts for most of streamflow during the dry summer. The associated nutrient inputs from these effluents have the cumulative effect of causing blooms of the filamentous green alga Cladophora, which forms large mats on the riverbed. The algae's photosynthesis during the day removes dissolved carbon dioxide (CO_2) from the water faster than the rate at which CO_2 in the atmosphere enters the stream water by reaeration. This causes the streamwater CO_2 to be out of equilibrium with the atmosphere and drives pH to values greater than 9.5, which exceed water quality standards. At night photosynthesis no longer occurs and the streamwater returns to equilibrium and to lower pH values, as shown in the figure below. In order to learn the maximum daily load of nutrients to achieve daytime pH values within water-quality standards, municipalities along the river required the detailed knowledge of the effect of nutrient enrichment on algal growth (47).*



The flow of many rivers below cities is either seasonally or perennially dominated by wastewater effluent (see Box 1 for example of impacts).

Background: Nutrients and Primary Productivity

Chemical inputs to flowing waters are from the atmosphere and watershed (i.e., substances carried by water that has entered via hydrologic routes). This "load" consists of both particles and dissolved substances (solutes). Solutes entering river ecosystems can be transported, transformed (change in chemical form), and/or retained. Chemical changes within stream ecosystems can be biological or physical/chemical.

Nutrients are those chemical elements required for growth of organisms. Animals obtain nutrients from the foods they eat. Plants, algae, and some bacteria are able to use inorganic nutrients for nutrition, and thus they provide the critical link between solute chemistry and the animal community. In rivers, nutrients of special interest are carbon, nitrogen, and phosphorus (C, N, and P), because these nutrients are major constituents of biological tissue and N and P are usually the least available relative to biological demand and can therefore limit productivity. In other words, such nutrients provide the resource base supporting growth of river biota. In contrast to the situation for eastern rivers and lakes, soils in much of the West are derived from parent material with relatively high P content; thus N is the limiting nutrient in many western streams and rivers, and even some lakes (17, 25). What this means is that additional inputs of N could over-stimulate productivity, especially in rivers without much shading from streamside trees. However, there are some watersheds that are poor in P (particularly in the Great Plains and Rocky Mountains), leading to P limitation there.

Productivity can be measured for autotrophic (self-feeding) or for heterotrophic (other-feeding) organisms. Primary productivity is the rate of synthe-

the necessity for storage structures. One of the most obvious anthropogenic changes in western watersheds is the extensive impoundment of rivers, creating lentic ecosystems where none previously existed, altering the tailwater reaches, and fragmenting riverine ecosystems (11). Because water is plentiful in some places (mountains) and scarce elsewhere (valleys), transfer systems route water from areas of low to high need. This alters the timing and volume of water and especially solute and particulate transport, and creates the illusion of a plentiful supply. In general, we have dampened high flows and augmented low flows, and the flow patterns that shape river ecosystems thus have been dramatically distorted.

At regional scales, changes in transport patterns can dramatically alter the chemical environment of rivers. Local diversion of water for municipal, agricultural, or industrial uses has immediate impacts on instream flow, but more far-reaching impacts on river water quality. Irrigation return waters introduce pesticides and fertilizer-derived nutrients into the aquatic system. Wastewater effluent contains high nutrient and organic carbon concentrations. Mine drainage is acidic and can carry high concentrations of toxic metals. Although these problems of water quality may be of restricted areal extent, they pose especially difficult challenges where water supplies are already limited.

sis of organic matter from inorganic materials. Primary producers in river ecosystems include algae and aquatic plants of the stream channel and trees, shrubs, and other plants of the riparian zone. Together with heterotrophic microorganisms (which are also users of inorganic N and P and are major consumers of organic C in both dissolved and particulate form), algae form the aquatic food base of most sunlit streams, whereas in small, heavily shaded streams, animal consumers feed on leaves from the riparian vegetation that decompose in the water. Physical retention of plant litter and its interaction with nutrients and decomposer organisms can also be critical for sustaining a diverse and functioning biotic community. Depending on the magnitude of riverine productivity relative to terrestrial productivity, river corridors can provide an important food base for terrestrial consumers (27, 50; Box 2).

Primary productivity in natural streams is controlled by physical conditions (such as temperature, light, sediment or soil structure, and current), supply of nutrients, direct consumption by grazing animals, and hydrologic disturbance (floods, drying). Inputs of toxic chemicals, such as pesticides or trace metals or excessive acidity (low pH), can poison the primary producer organisms and thus alter productivity. Increased nutrients can lead to enhancement of primary productivity. In many cases this is undesirable because harmful (certain blue-green algae) or nuisance (heavy mats of filamentous green algae) blooms can occur. Algal community structure can be altered, resulting in potential loss of rare animal species that depend on specific algal foods. Such alteration in algal communities may be nonsustainable, increasing the percentage of species that are rare or endangered. High rates of primary production can also cause large increases in pH during the daylight period and noncompliance with EPA water-quality standards (Box 1). Further, high levels of nitrite-N and ammonium-N (inorganic forms of N) are toxic to fauna and to humans, especially young children. Finally, excessive organic C input stimulates decomposition, which leads to reduction in oxygen concentrations of water and a host of consequences, such as kills of aquatic insects and fishes that are dependent upon aerobic (oxygen-rich) environments.

In addition to potential control of primary productivity and community structure by nutrients, there is a reciprocal influence of primary producers on the chemistry of river water. More precisely, lotic (riverine) ecosystems have the ability to retain nutrients through the activities of organisms (primary producers and heterotrophic microorganisms). Nutrients are taken up by algae, aquatic plants, riparian plants, or heterotrophic microorganisms. The assimilated nutrients are eventually deposited in stream sediments or on floodplains or stored in long-lived organisms, and therefore retained. Nutrient retention is a property of river ecosystems wherein nutrient concentrations in streamwater are changed in an up- to downstream direction. This ecosystem property, or "ecosystem service" (14, 42) has been long exploited by humans, and is often referred to as "self purification" of rivers. Natural and constructed wetlands also exhibit nutrient retention, and are therefore valuable to society in improving

(Box 2) Indicators of the relative importance of terrestrial vs. aquatic food supplies to animals in mesic and desert ecosystems. Primary productivity of the terrestrial system vastly exceeds aquatic primary productivity in mesic regions, whereas the reverse is true of deserts. In deserts, estimated insect emergence from streams provides an important food resource for terrestrial consumers (27). All rates are in mg $m^2 \bullet d^1$, and are calculated from literature values.

	Mesic	Desert
Terrestrial Primary Productivity	6,000	200
Aquatic Primary Productivity	10-200	5,000-10,000
Aquatic Insect Emergence Rates	1-19	80
AQUATIC:TERRESTRIAL	0.002-0.3	25-50

water quality (17). High nutrient loads from watersheds to rivers are of concern when inputs exceed this retention capacity. If this occurs, recipient systems lose biological sustainability, becoming subject to eutrophication or toxic levels of nutrients. Receiving systems include groundwaters (which in drier regions are recharged through stream beds), lakes, reservoirs, lower mainstem rivers, bays, estuaries, and coastal marine ecosystems.

Part of the nutrient-retention function of rivers involves decomposition of the organic carbon load (both particulate and dissolved) introduced from upland ecosystems. Decomposer organisms consist primarily of bacteria and fungi. During decomposition, these microbes use carbon from the source material and may take up additional nutrients from the water. Aerobic decomposition requires oxygen and thus there is a biological oxygen demand (BOD) associated with decomposition of organic material. This decomposition is a fundamental biological process essential to the health of any ecosystem; in heavily shaded streams, the microbes are an important food base for aquatic consumers. The BOD of aquatic systems is of concern when it becomes so elevated that oxygen in the water drops to low levels or is consumed completely, leading to mortality of fishes and other animals.

Historical Conditions in Western Rivers

Climate, hydrology, and geomorphology provide a physical template for ecological activity in lotic ecosystems. Climate of the West is varied, but with important exceptions (Pacific Northwest), it is dry. This has been true at least since the last glaciation, with minor cycles of wetter or drier periods appearing in the record. While some changes in aquatic ecosystems have been attributed to climatic variation (12), much more dramatic alterations in the structure and function of rivers of the West have occurred since settlement by Europeans. Over the past 10,000 years, large aquatic ecosystems, including once-extensive lentic ecosystems (lakes) and rivers, decreased naturally until European humans arrived less than 200 years ago. Since that time, all those habitats plus once-widespread, associated wetlands, including marshes, and riverine riparian zones, have decreased far more rapidly, decimated by human alteration (38). Historically, geomorphic processes, rather than human intervention, controlled river-channel form. Large floods shaped river channels by scouring sediments from pools and depositing them on riffles and lateral gravel bars. Interaction of riparian vegetation and the complex river networks created a diversity of riverine habitats that varied in energy inputs supporting productivity (sunlight, terrestrial organic-matter inputs), organic-matter storage, rates of nutrient transformation, substrate materials, degree of connection to the river and to subsurface waters, and oxygen concentration. The balance between retention and transport for riverine corridors was a function of the collective retention capacity of this diversity of habitats.

Several known historical conditions are of direct relevance to the interaction among nutrient retention, nutrient transport, and primary productivity. We know that the river and its floodplain were once more directly connected hydrologically. Because flow was neither regulated nor confined, floodplains or riparian zones were more expansive and periodically flooded (e.g., 10, 44). Retention of solutes and particulate materials must have been greater then because floodplain and oxbow lakes, wetlands, and woody debris accumulations were prevalent. These features increase structural complexity, retard transport, and enhance the likelihood of anoxic conditions. Many nutrient transformations, some resulting in loss of nutrients from the ecosystem, occur in such anoxic (oxygen-poor) microhabitats. Even small mountain streams without extensive floodplains experienced large and frequent inputs of wood from the surrounding forest, including those caused by beaver activities. Wood inputs also increased channel complexity and thereby promoted nutrient retention. In southwestern grasslands, before massive arroyo-cutting events of the late 1800's, streams were characterized by more extensive floodplains, with abundant marshes, ponded areas, and organic matter storage (26).

Flooding was a natural disturbance that periodically "reset" these stream and river ecosystems. Flooding rearranged the channel, enhanced connection between stream and floodplain, moved sediment, and enhanced riparian development, sustaining a process of "perpetual succession" in riparian and channel biota. Studies of World rivers have demonstrated that river productivity increases after major floods, and long-term, low-flow conditions decrease productivity (30, 53).

State of Knowledge

Current knowledge and our discussion of nutrients and primary productivity are extrapolated mainly from studies of small streams. We understand some properties of river ecosystems very well (i.e., we can make statements with high confidence) and others not as well. Statements summarizing key elements of this understanding are presented here in an approximate order of decreasing confidence.

Many streams in the arid/semi-arid West are unshaded by riparian or forest vegetation, thus primary productivity is naturally high. Where streams are heavily shaded (e.g., mountains, Pacific Northwest), primary productivity is naturally low until streams widen sufficiently to admit sunlight. Deforestation in the riparian zone of shaded streams drastically alters their structure by shifting them from detrital (based on organic input from the watershed) to an algal food base.

Nitrogen limitation is common in many western streams; thus, water-quality standards regulating N inputs may be more important to maintenance of natural rates of primary productivity than those focused on P inputs. Agricultural landuse increases N input to streams and groundwaters. Human loadings of P may affect primary productivity after N is added via those same inputs, and the combined contributions of both N and P can lead to even greater eutrophication.

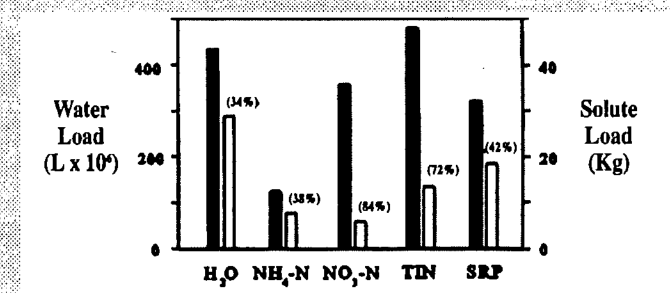
The hydrologic regime is particularly important in a cycle of resetting/successional events that determine the temporal bounds of productivity and nutrient-retention. Natural variability in hydrologic regime (both floods and low flows) is key to sustaining ecosystem function in western rivers.

Nutrient retention is a functional property of linked surface, hyporheic, riparian subsystems, and is dependent upon hydrologic connections among them. Disruption of these hydrologic connections will change nutrient-retention capacity (Box 3). The effects of hydrologic regime and the hydrologically linked subsystem structure are interrelated, because periodic resetting of biomass maintains the system in a retentive state. Nutrients can be stored in biomass only if biomass is accumulating or soil storage is increasing. A mature riparian forest that is not increasing its storage of nutrients has no long-term capacity for net retention of nutrients in biomass (e.g., 51).

(Box 3) ***Experimental Floods in the Rio Grande Bosque as a Restoration Technique. H. Maurice Valett.*** *The flood-pulse concept (5, 30) emphasizes that lateral interactions between rivers and their riparian forests create and maintain the structure and functioning of river/floodplain ecosystems (7). Except for the Yellowstone in MT, all large rivers in contiguous USA have been severely altered for hydropower and/or navigation. In fact, disconnection of river channels from their historic floodplains is a severe ecological problem in the USA and Worldwide.*

Along the Middle Rio Grande, NM, flow regulation has isolated riparian forests (bosques) from flood pulses for the past 50 years (13). Only restricted areas within floodplain levees are still inundated on an annual basis. In absence of flooding, decomposition rates have been drastically decreased (35) and massive amounts of forest-floor carbon (branches, litter, fallen trees) have accumulated in areas not inundated by floods (16). This debris represents a substantial threat to the ecology of the river/floodplain system as fuel for fires. Recently, fires destroyed more than 5,000 acres of the Rio Grande bosque, an ecosystem in which fire has not historically played an important ecological role.

Severing the interaction between a river and its floodplain may also have strong implications for nutrient retention and water quality. Experimental flooding of an isolated bosque showed that both water and solutes were retained by a 20-acre experimental plot. Greater masses of inorganic N and P were retained during flooding than could be attributed to water loss to the subsurface (see figure below). These data indicate that biological and chemical processes on the flooded forest floor remove solutes from floodwater and increase water quality. Under natural conditions, the floodplain forest and river water exchanged materials and energy extensively, a linkage that promoted ecological processing in both that forest and aquatic ecosystems (35).



Inputs (solid bar) and outputs (open bar) of water (H_2O), ammonium-N (NH_4-N), nitrate-N (NO_3-N), total inorganic N (TIN), and soluble reactive P (SRP) during experimental flooding of a 20-acre plot of isolated riparian forest. Values in parentheses are retention (load in - load out) as a percentage of input load.

Most water-quality models applied to larger rivers focus on phytoplankton production in the water column and ignore benthic primary production. Many stream reaches, even in large rivers, include extensive shallow riffles where algae on the stream bottom is the major source of production and nutrient uptake.

Reservoirs, now common features of the landscape, function completely differently than free-flowing rivers in terms of the balance between retention and transport. They are organic mat-

(Box 4) ***Impact of mining on stream-water quality and stream ecosystems: A case study of St. Kevin's Gulch, Lake County, CO, by Diane M. McKnight.*** *Mining for silver, gold, and other metals around the turn of the Century (1880-1920) has left a legacy of small abandoned mines scattered throughout the Rocky Mountains. Drainage of these mines contributes metals and acid to many headwater streams, and cause acidic conditions and precipitation of iron (Fe) oxides (referred to as "yellow-boy") in the stream bed. These mine-drainage streams can support substantial growth of filamentous green algae that tolerates acid conditions and high metal concentrations. For example St. Kevin's Gulch near Leadville, CO, has a pH of 3.5, concentrations of dissolved zinc of 8.0 mg/L, and develops abundant mats of* Ulothrix sp. *(a green alga) in summer. As for all algae, that growing in St. Kevin's require P for growth; however, the precipitated Fe oxides in the streambed also have a high capacity to chemically sorb P (as phosphate) at low pH. Photoreduction of the Fe oxides in the streambed is an important control on the bioavailability of P to* Ulothrix *because the photoreduction during the day releases the sorbed phosphate, which is then rapidly assimilated by algae downstream. Iron oxides move as colloids and as particulate material for large distances downstream in mine-drainage-contaminated river systems such as the Arkansas River, into which St. Kevin's Gulch flows. It is probable that this connection between the photoreductive cycling of Fe and P availability is significant, as the nutrient occurs in both low-order and larger streams. Many abandoned mines are at high elevations in remote locations and progress towards remediating them will be slow. Thus, interactions between P and Fe biogeochemical cycles in these systems will continue to be significant in nutrient transport for some time.*

ter and nutrient traps rather than processors. Organic matter delivery to reservoirs contributes along with inorganic sediments to filling them, but also can results in enhanced decomposition and anoxic hypolimnia (leading to fish kills).

Status of Monitoring and Database

The NAWQA Program currently supports water quality analysis in 14 watersheds of the West. Sampling in nine of these began in 1991, five watersheds were added in 1994, and eight are scheduled for a 1997 start. The sites are well distributed, and monitoring has focused on nutrients. From this work, we know:

- All 1991 study basins have high nitrate-N in groundwater and surface water associated with agricultural landuse (43).
- Nitrogen deposition from the atmosphere is high in CA, in northwestern UT, and along the eastern margin of the West (as defined for purposes of this commission).
- Nitrogen and P inputs from fertilizer and animal manure are highest in CA's Central Valley, in eastern WA, and along the eastern margin of the region.
- Elevated trace metals in streams draining areas with mining are concentrated in mountainous regions, the Rockies and Sierra Nevada.
- Municipal uses of water and wastewater effluent are primary water-quality issues for the South Platte, AZ basins, Sacramento, and Puget Sound study areas.

The NSF supports a network of 18 Long-Term Ecological Research (LTER) Sites, of which eight are located in the West. Not all these sites support research on streams and rivers; those that do have a strong lotic research component include H.J. Andrews in the Cascade Range of Oregon, Konza Prairie in KS, and the Arctic LTER in AK. The NSF also has supported a long-term stream project in central AZ (Sycamore Creek) through its Long Term Research in Environmental Biology Program. The GS supports long-term research on headwater stream ecosystems in the CO Rocky Mountains, which are representative of source waters for larger rivers of the Southwest. Loch Vale watershed is a pristine watershed in Rocky Mountain NP that is drained by Icy Brook. The long-term studies of two streams influenced by metal contamination from mining, a tributary to the Snake River and St. Kevin's Gulch, have illustrated important controls on nutrient transport by iron-oxide contaminants (Box 4). Long-term research on rivers as ecosystems, however, is not extensive.

Present Conditions

Several aspects of the current status of rivers in the West differ dramatically from historical conditions. In general, the extent of modification may be greatest for larger rivers, such as the Columbia, Colorado, Rio Grande, Snake, South Platte, Missouri, Sacramento/San Joaquin, and others, which are subject to all of the modifications imposed by multiple uses of rivers and river water (point-source discharges, impoundment, hydroelectric generation, irrigation diversion, riparian conversion, interbasin water transfer, introduced species, etc.). To summarize:

a) All large rivers of the West are impounded. Productivity thus has shifted from riverine to lentic productivity associated with large reservoirs, and the historic balance between retention and transport has been altered. Flows downstream from dams are highly regulated, often imposing a completely different hydrologic regime on the river (11).

b) Riparian zones are in decline. Associated with this is loss of historic connections among subsystems of the riparian corridor (riparian zone or floodplain wetlands, hyporheic zone, surface stream, off-channel water bodies), and loss or deterioration of ecosystem services: provision of habitat for wildlife and fishes, and the retention-transport function of rivers. For example, due to management of river flows, the extensive floodplain wetlands within the Rio Grande system were virtually eliminated between 1918 and 1989. Represented by marsh, open water, saltgrass meadows and alkali flats, wetlands occupied nearly 52,000 acres along the Middle Rio Grande in 1918. By 1989, only 7% (3,671 acres) of this land still supported wetlands (13).

c) Floodplains have been constricted, leveed, and paved. The ability of rivers to renew themselves during high flows has been greatly diminished. Accelerated flow of flood waters in straightened and simplified channels increases peak flows and transfers the enormous force of floods to downstream areas and landowners.

d) A major land-use in the West is irrigated agriculture. Irrigation of crops accounts for most of the water consumption and is responsible for groundwater declines, particularly in the Southwest. For example, the GS documents groundwater decline of greater than 30 m in the Rio Grande Valley near Albuquerque, NM, due to irrigated agriculture (48). Further, application of Nitrogen-rich fertilizer on irrigated farmlands has increased dramatically since 1950 (43), leading to enrichment of surface- and groundwater that drains fields. Dewatering and agricultural inputs have both increased the solute and particulate load carried by rivers and changed transport characteristics.

(Box 5) Groundwater extraction for municipal use along the Rio Grande has increased drastically during this Century. Between 1960 and 1992, groundwater pumping by the city of Albuquerque increased from 14,000 acre-ft/yr to more than 118,000 acre-ft/yr. The result has been a drop in water-table elevation of 42 m in the east Albuquerque area (48) that has reversed the direction of subsurface flow between the river and its aquifer.

e) Timber harvest in headwaters has altered hillslope and riparian forests, increased rates of landslides, increased sediment and nutrient inputs, increased stream temperatures, removed large wood, and decreased pool habitats and other critical habitat elements (23, 39). Regional land-management policies have been to developed to address larger landscape patterns and processes, including the functions of river networks and riparian corridors (19). Growth of cities is associated with increasing groundwater use and changes in river water quality (Box 5).

f) Large areas of the West (70%) are grazed, yet much of this land is marginal (low animal production) for such use. Grazing is particularly destructive in sensitive riparian corridors (21), preventing recruitment of trees, causing streambank erosion, and again altering balance between retention and transport (Box 6). Other upland landuses, including mining and deforestation have increased erosion, altered the chemical quality of water, and changed primary production.

Prognosis

Failure to understand and incorporate measures to maintain the balance between transport and retention will results in loss of sustainability of river-ecosystem structure and function. If the retention capacity is exceeded, the effect will be to transfer water-quality problems to recipient systems: reservoirs, groundwaters, and estuaries (e.g., 41).

The USA is near the quantitative limit of its water resource. In the arid West the limit is probably exceeded if sustainability is a necessary goal. Some will argue this point, but none can argue that as the quantitative limit is approached, water-quality issues become more important. At times and in critical places the issues are urgent. Management errors are more common, the effects of the errors are more complicated to remedy; they are more widespread, and longer lasting.

Nevertheless, as problems gain urgency, opportunities for restoration and management are beginning to appear. Sensitive environmental management ideas are emerging in the Colorado River basin under the demands of the ESA, the Grand Canyon Protection Act, and the Glen Canyon Dam Environmental Impact

(Box 6) ***Grazing impacts on water quality and the balance between nutrient transport and retention, by H.M. Valett.*** *The federal government is responsible for approximately 316 million acres of land in the 11 westernmost states and livestock grazing is permitted on ~90% (288 million acres) of this terrain (2). Grazing also occurs on over 200 million acres of private land in the West. Thus, livestock grazing represents the most widespread land-management practice in western USA, and is ongoing in wilderness areas, wildlife refuges, national forests, and some national parks (21).*

Considerable evidence shows current grazing practices adversely affecting bank stability (31), decreasing stream water quality (9, 15 28, 46), and reducing aquatic primary productivity (2). This is particularly true for watersheds of the semi-arid Southwest, where vegetation plays a critical role in determining the nature of runoff and sediment transport (3). Overgrazing of stream banks resulting in reduction of ability of plants to trap sediments, sloughing of banks, and increased channel widening in a northern AZ cienega/stream system (40). Livestock grazing resulted in increased total dissolved solids and elevated fecal coliform bacteria when comparing grazed and ungrazed reaches of a stream in the CO front range (29). These and other studies suggest that grazing impacts stream ecosystems directly because cattle seek out stream habitats for water, shade and thermal cover (1), and indirectly by altering the nature of linkages between riparian zones which further influences upslope terrestrial environments and the stream ecosystem itself. Throughout the Southwest grazing impacts have exacerbated arroyo formation and sediment loss from semi-arid watersheds (21, 31, 34). This is particularly true for Rio Puerco basin of north-central NM, where grazing and drought interacted to incise the river by more than 15 m since the late 1800s (34). As a result, the Rio Puerco has one of the highest suspended sediment loads for any river in the World and contributes more than 50% of the total sediment load in the Rio Grande into which it drains, while providing less than 20% of the water (22). Retention of sediments and nutrients in this system are critical issues for water quality in the Rio Grande and its reservoirs.

Current perspectives of nutrient retention in streams and rivers also recognize the importance of interaction between above-ground stream water and shallow areas of saturated sediment (i.e., the hyporheic zone) that are in close contact with channel water (6, 49). When water enters the hyporheic zone, contact time with the biota and particles of the stream bottom and aquifer is increased (20), and biological and chemical processes more effectively remove nutrients from solution and increase their retention. Using chemical tracers and nutrient-transport models, the extent of stream-groundwater interaction in a tributary of the Rio Puerco was shown to be an order of magnitude higher in a study reach where livestock grazing was excluded when compared to an adjacent reach affected by grazing (45). Loss of instream vegetation, compaction of sediments, and alteration of channel structure were proposed as mechanisms by which cattle altered this important interaction between stream and shallow groundwater.

Statement (8). Adaptive management, a process that connects science, management, water policy, and public interest (32), has gained attention in the Columbia basin and is being implemented on the Colorado (Box 7).

(Box 7) Since 1963, when Glen Canyon Dam closed the Colorado River, dramatic changes have been occurring in Grand Canyon. Annual high flows were reduced, annual low flows were no longer so low, and variability was suppressed. The sediment load was greatly reduced, and river temperature was constantly low. A trout fishery developed, camping beaches for river runners were being eroded, native fishes became endangered, riparian vegetation increased, woody debris disappeared, and sediment contributed by tributaries was deposited in the channel rather than on channel margins and in eddies. Clearly, the absence of annual flooding was a major disturbance to this ecosystem. Many riparian features and most inchannel habitats depend upon sediment distribution, sediment distribution is controlled by the flow regime, and the flow regime is now controlled by the dam. A flood release from the dam was a logical approach for management if details of this interdependent sequence was understood well enough to design the magnitude and duration of the floodflow. Research provided sufficient detail. In 1996, 1,274 m^3/second of Lake Powell water was released deliberately from Glen Canyon Dam to test ideas about restoring some of these features in the Grand Canyon river corridor. The flood magnitude, about half of the unregulated mean annual flood before the dam, and duration, seven days, were comparatively small. Early results confirm predictions, but long-term monitoring continues.

Issues and Recommendations

ISSUE: Many land and water management practices sever the connection among interdependent subsystems of rivers: stream, riparian, floodplain, and hyporheic zones.

This is especially true of irrigated agriculture, livestock grazing, channelization or confinement of rivers, many forestry practices, and urbanization. The consequences of disrupting this linkage are reduced nutrient-retention capacity, shifts in the energy base of forested streams from dependence upon inputs from the surrounding watershed to instream primary production, sedimentation, and clogging of the streambed, which alters nutrient processes, and massive accumulation of organic matter in floodplains (see Box 3).

- ***RECOMMENDATION: A natural or imposed (but realistic) flooding regime (4, 30) will re-establish the cycle of resetting successional events that allow nutrient retention.***

To the extent possible, riparian forests should be left intact or restored, and rivers permitted to overflow their banks into the floodplain. The idea is to let the river perform its services through maintenance of the critical hydrologic connection among surface, subsurface, and off-channel subsystems.

ISSUE: Impoundments trap nutrients and sediment, disconnect river segments, isolating lower river reaches from forested headwaters, and create lentic habitat where none previously existed.

The historic retention-transport balance is completely changed. Consequences of this include eutrophication (over-enrichment) of reservoirs, which can lead to more rapid reservoir filling, altered community structure (different organisms), and anoxic conditions and other water-quality problems within reservoirs. Downstream, sediment supply is depleted, creating erosional habitats that favor certain organisms over others, and nutrient inputs to recipient systems change in terms of timing and form.

- ***RECOMMENDATION: The feasibility of decommissioning dams should be investigated on a case-by-case basis.***

We recommend feasibility be based on a cost-benefit analysis that: **a)** incorporates the value of river ecosystem services; and **b)** incorporates a mitigation plan for a potentially massive sediment release following decomissioning.

ISSUE: Dam management drastically alters river flow patterns, changing historic hydrologic regimes.

This affects the riparian-stream-hyporheic connection as well as successional patterns in the river and floodplain. An excellent example of the consequences of uncoupling the river and floodplain is the invasion of saltcedar in southwestern rivers. With a disconnected floodplain, water tables drop, favoring invasion of this exotic species. Water quality is affected because the trees essentially salinize riparian soils, preventing growth of native plants (10). Another consequence of eliminating flooding disturbance is massive accumulation of biomass in the river and riparian zone with no periodic export (see Box 3). Complete reversal of flow seasonality often results from impoundment of water for irrigation. This has consequences for community structure of primary producers, as well as rates of nutrient transformation. Finally, even diel variations in flow rate result from some (e.g., hydroelectric) dam operations.

- **RECOMMENDATIONS: Allow periodic flood flows.**

Flood flows will: **a)** reduce organic matter accumulation; **b)** redistribute sediment; and **c)** re-establish river-floodplain connections, at least episodically (see Box 7). Minimize diel variability in flow. Redesign outlets from dams. Examine a broader range of operational options to meet river management and restoration goals. Decommission dams where possible (for example, the Elwha Dam in Olympic NP is scheduled to be dismantled; 11).

ISSUE: The need to irrigate farmland leads to reliance on groundwater, interbasin transfers, and overdrafts.

Many examples exist in the Southwest and CA. Consequences of groundwater withdrawal to support irrigated agriculture are water-table decline, loss of riparian zones, and loss of perennial springs and streams. Diversion and irrigation wastewater returns result in declines in water quality and eutrophication of rivers and/or recipient ecosystems. All river ecosystem functions, transport, habitat provision, biotic production, retention, are adversely affected.

• ***RECOMMENDATIONS: Agricultural landuse needs to be designed with a broad, landscape perspective that has as part of its goal the preservation of ecosystem services such as retention or nutrient filtration by riparian zones and provision of habitat for water-dependent species.***

Much of the solution may require changes in water law. Water law currently favors agriculture over other uses because of its historical priority, and the practice is overly subsidized. As a result, water is too cheap, making a marginal practice profitable in many areas. Pricing encourages consumption rather than rewarding stewardship and conservation. Again, a cost-benefit analysis that values river ecosystem services and looks at long-term (sustainable) projections is needed. An example of such an analysis, revealing the recreational value of water use alone to equal or exceed that for irrigated agriculture during low-flow periods, has been described (42).

ISSUE: Effluent is the major or even sole source of flow in rivers below urban centers.

This results from: **a)** complete utilization of water supply upstream and laws that permit no flow (e.g., Phoenix, AZ); and **b)** discharge of treated wastewater into river beds. Consequences include eutrophied water courses, infiltration of high nitrate-N water to groundwater, the possible transport of infectious agents, and delivery of all of these problems to recipient systems, such as estuaries and the coastal ocean. With eutrophication, new water-quality problems arise, such as pH in excess of standards (see Box 1). On the positive side, water supply in otherwise dry channels supports the growth of riparian vegetation and aquatic biota.

• ***RECOMMENDATION: A strict regime of point-source and non-point source management is required.***

Maintenance of instream flows is needed to partially accommodate the point-source input of nutrients represented by wastewater effluent. Restoration plans that reestablish hydrologically connected river-riparian ecosystems should be encouraged.

ISSUE: Riparian ecosystems are under threat due to species invasion, overgrazing, groundwater withdrawal, diversion, and deforestation.

These ecosystems are integral components of rivers, and play an important role in nutrient retention. They are generally productive, and thus attract many desirable birds and other animals. In forested watersheds, riparian forests directly supply the food base of streams.

• ***RECOMMENDATION: Riparian corridors should be protected and restored as part of river systems.***

This may involve isolation from grazing and exclusion from logging. Plans for riparian protection should not be independent of those aimed at river protection; indeed, we recommend that riparian protection be based within a regional-scale concept of landscape management.

ISSUE: Research needs are many; research attention and focus has been inadequate to the task of restoration of nutrient retention and productivity functions of river ecosystems in the West.

For example, there are few long-term studies of rivers as whole ecosystems. Monitoring of rivers in the West is probably not dense enough, given the great diversity of climatic, geomorphic, and hydrologic conditions. Specific experiments in restoration tactics have not been performed; thus, implementation of management practices is guesswork at best.

• ***RECOMMENDATION: Monitoring programs should be integrated to emphasize ecosystem quality, not solely water quality.***

This could be done within networks such as NAWQA or LTER, and these need to be expanded. Research support for investigations of nutrient retention and river-riparian productivity of restored or managed ecosystems is a priority.

ISSUE: Water law and management policies are not designed to protect sustainability of whole river ecosystems, whole basins, or landscapes.

• ***RECOMMENDATION: Specific changes that protect river functions are needed in water management policy and water laws.***

Examples are: **a)** subsidies to irrigated agriculture should be reduced or eliminated; **b)** minimal instream flows should be maintained; **c)** hydrologic variability should be maintained or re-established; and **d)** surface- and ground-water laws should be linked.

Conclusions

We advocate a large-scale (e.g., regional) approach to policy and management that views rivers as the transport and retention systems of landscapes. This approach must be based in realistic cost-benefit analyses that assign value to the services performed by river ecosystems (e.g., 14). There is critical need to bring ecology into policy and management decisions (37). The past focus has been on water resources (largely in terms of availability), economics, single-species biology, and species diversity; now is the time to bring other elements of biodiversity (landscape diversity, process diversity) and issues of ecosystem services into the picture. River management should be considered from a four-dimensional perspective (52). This includes consideration of physical-chemical and biological linkages that exist laterally (riparian<—>channel), vertically (hyporheic/ground water<—>surface water), longitudinally (upstream<—>downstream), and temporally (present<—>historic conditions). Together these connections sustain biotic structure and function through a balance between retention and transport.

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CHAPTER V: SUSTAINING WESTERN AQUATIC FOOD WEBS

BY

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Introduction

Citizens of the USA increasingly value the diverse natural landscapes of the American West (henceforth, "the West"), and the natural ecosystems and native species these landscapes support. Biodiversity conservation often focuses on the more conspicuous vertebrates like fishes, birds, or mammals, which are of commercial, recreational, or spiritual value to various constituencies. In order to maintain such species, the food webs that in turn sustain them must also be preserved. All life in rivers and lakes depends on energy derived from "primary producers" (algae and higher aquatic plants that harvest sunlight and nutrients), or from terrestrial detritus (dead organic material) that entersthe aquatic habitat and is consumed by fungi, bacteria and other "detritivores." Primary producers and microbial detritivores are foundations for food chains, in which organisms at higher trophic levels (e.g., predators) consume organisms at lower trophic levels (e.g., detritivores and grazers) that in turn eat plants, detritus, and associated microbes. The chain is really better thought of as a web, as feeding relationships among organisms are complex. All aquatic life is woven into this web. While we rightfully are concerned with the larger, charismatic, commercially important organisms like salmon, we also need to protect and preserve the invertebrates and microorganisms that sustain them.

Here we discuss intermediate consumers in these food webs as critical resources, not only for their roles in supporting organisms of greater public interest and recognition, but also for other ecosystem services, their own intrinsic value, and for their potential to serve as "sentinels" indicating when and where environments are deteriorating.

Organisms in "Healthy" Food Webs as Critical Resources

Aquatic Food-web Structure and Function (A Primer)

In aquatic food webs, smaller organisms are typically eaten by larger ones. This size structure contrasts with common patterns in terrestrial webs, and arises because of constraints and opportunities of life in water. Aquatic plants float, so there is no need for rigid stems or trunks to reach the light. Further, small plants with high surface-to-volume ratios can more easily acquire dissolved nutrients. For both reasons, aquatic primary producers like algae often are tiny and have very high reproductive rates. Aquatic predators typically lack grasping appendages with which to tear prey apart before swallowing it, because such appendages are hydrodynamically costly. Therefore, predators are "gape-limited," consuming only the prey items they can fit in their mouths. Gape-limited animals in aquatic webs thus tend to increase in size and longevity from lower to higher trophic levels. These features commonly lead to inverted trophic pyramids in aquatic ecosystems, where small biomasses of fast-growing plants and microbes with rapid turnover support larger biomasses of longer-lived, larger animals.

The efficiency with which energy and nutrients are routed up through food webs depends largely on characteristics of the consumers at intermediate positions between primary producers (or detritus and microbes, the other major energy sources) and top predators such as fishes. If these consumers efficiently harvest plant or microbial production and also are vulnerable to predation themselves, then energy and nutrients pass quickly from rapidly growing plants and microbes through herbivore-detritivore consumers (typically invertebrates like aquatic insects), to be stored in the bodies of slower-growing, longer-lived predators (typically vertebrates like fishes).

Linkages Among Aquatic Ecosystems and Watersheds

Surface-water habitats are inextricably linked to their watersheds in both arid and humid regions of the West by hydrology, chemistry, sediment, and organic-matter transport. Inputs from watersheds strongly affect aquatic food webs, and therefore the river-watershed exchanges mediated by organisms. Export in the other direction, from aquatic to terrestrial ecosystems, is particularly crucial to terrestrial consumers in arid environments (57). Two important groups of intermediate consumers, aquatic insects and amphibians, have complex life cycles that link aquatic and terrestrial food webs.

Larval aquatic insects support aquatic predators like fishes, then emerge as winged adults to feed terrestrial invertebrates, reptiles, amphibians, birds, and mammals (12, 48-49, 57, 107, 123, 153-155). Amphibians reproduce and live as larvae in water, while adults typically spend much of their life on land.

Ongoing degradation and loss of surface-water habitats, due primarily to human activity, threaten or damage populations of aquatic organisms throughout all 19 western states. While concern for native species is growing, interest in maintaining ecological services and economic benefits of "healthy" rivers, lakes, springs, and wetlands is already nearly universal. Here we present a scenario suggesting how food webs should function in "healthy" aquatic ecosystems. We then review selected cases to illustrate how human impacts on the landscape affect these webs by altering habitats and lives of their constituent organisms and ecosystem services these plants and animals perform.

Ecological Services Provided by "Healthy" Aquatic Food Webs

Ecosystem "health" is difficult to define across a region as broad and diverse as the West because of variations in biogeography, climate, and geology. One generalization relevant to aquatic ecosystems, however, is that those which are healthy have features that retain and recycle nutrients within local watersheds. Well-vegetated watersheds, for example, slow or prevent nutrient losses from the land (50, 116). Energy and nutrients that do reach "healthy" aquatic food webs tend to be routed up through consumers to be stored in the bodies of long-lived predators, as just described. These "top-heavy" food webs buffer watersheds by preventing pulses of nutrients that periodically wash into channels (e.g., during rainstorms) from rapidly flushing down drainage networks, where they accumulate and can contaminate water bodies downstream (Box 1; 15).

In addition to buffering ecosystems by storing nutrients, vertebrate predators are active and mobile. They therefore can resist being swept downstream, and retain nutrients locally. Some, in the course of diel, annual, or life-history migrations, translocate nutrients many kilometers upstream (e.g., migrating adult salmon; 5, 16, 87) or upslope into the terrestrial watershed (e.g., bats foraging on river insects and roosting in caves or trees; 123). In these ways, native fishes and other vertebrate predators feeding on aquatic production help retain and restore fertility in upper parts of watersheds, further reducing the potential for eutrophication of downstream wells, lakes, and estuaries.

Two factors appear crucial for maintenance of "healthy" aquatic food webs. First, rivers in general and Western rivers in particular require quasi-natural hydrologic regimes with periodic flooding for maintenance of healthy, indigenous ecosystems (33, 81, 90, 121-122, 133, 151). Western river biota evolved under extreme hydrologic fluctuation, over time scales of millenia (53). Native species can typically resist or recover from scouring floods or dewatering droughts if watersheds contain the second crucial factor: structure that provides refuge in slow water during high flow or any water during drought (42). Types of refuge vary longitudinally in river networks, among regions, and across habitat types, but include hyporheic habitats (water-filled spaces below the surface of the river bed); woody debris jams or beaver dams and associated pools; and off-channel habi-

Box 1. The length of functionally significant food chains can be counted as the number of trophic levels that are alternately released or suppressed following the removal of a top predator. Organisms constituting a particular trophic level can, if not suppressed by their own predators, potentially regulate (prevent outbreaks) of their prey or resources at the next lower trophic level. Severe environmental degradation often shortens functional food chains to the point where this buffering capacity is lost. A worst-case scenario has occurred near the outskirts of Phoenix, AZ, where water wells have been shut down due to toxic accumulations of nitrates. Residents in the region are literally drinking their own automobile exhaust (S. Fisher and N. Grimm, in 67). Food webs in the arid, eroded, over-grazed watersheds collecting this well water can be argued to have no functionally significant trophic levels—i.e., riparian and aquatic primary production is insufficient to sequester nitrogen into plant biomass. If watersheds support sufficient plant growth, water wells may remain uncontaminated, but eutrophication may become a problem if macrophyte or algal accrual is excessive. Grazers may help to regulate plant accrual, but if uncontrolled, could give rise to nuisance outbreaks of insects. Predatory invertebrates and small fish (three trophic levels) will improve the situation, and if these and the grazers feed larger fish, birds, and wildlife, recreational and aesthetic values of the ecosystem are enhanced. Longer food chains are often positively associated with environmental quality and biodiversity, unless they result from introductions of alien species which can have unanticipated, adverse effects on native biota.

tats. Off-channel aquatic habitats were once much more widespread. They include undercuts beneath banks stabilized by riparian vegetation; off-channel pools, backwaters, and interconnecting secondary channels; and marshy floodplains, inundated by high water, which damped discharge peaks and stabilized and retained sediments.

Historic and Ongoing Degradation of Habitats and Food Webs

Historic Changes. Across the West, a general pattern of deterioration of surface-water habitats followed clearing of forests, plowing of grasslands, and introduction of livestock. As vegetation that retained sediments and absorbed runoff was lost, floods and flood-borne sediments eroded watersheds and caused widespread gullying and downcutting of rivers. Positive feedback followed as entrenchment (downcutting) of rivers lowered water tables, sometimes several meters, further stressing riparian vegetation. These conditions were exacerbated by roads, mining, agriculture, and other activities that choked rivers with unnaturally high sediment loads, and in some cases chemical pollutants.

These changes simultaneously eliminated critical features of rivers that served as refuge for biota from hydrologic variation. Marshlands (ciénegas) that had moderated fluctuations, retained and recycled nutrients, and served as refuges, nurseries, and rich feeding grounds for aquatic animals, were lost to grazing, and then to desiccation as channel downcutting, flow diversion, or groundwater mining for agriculture lowered water tables. Flood flows confined in entrenched channels or behind man-made levees focused erosion on streambeds, deepening scour (90). Hyporheic habitats were lost as gravel beds were eroded to bedrock or choked with excessive fine sediments. Refuges and pools provided by beaver or log jams were lost as beaver and trees were unsustainably harvested (79, 129-131).

Ongoing stresses. Historical degradation of surface-water habitats has left their biota even more vulnerable to present-day stresses. Ongoing practices which continue to degrade aquatic ecosystems (102) include:

- flow regulation, diversion, and groundwater mining, which distort hydrologic regimes and eliminate, simplify, or fragment habitats;
- deliberate or inadvertent introductions of alien species;
- unregulated mining, agriculture, grazing, and timber harvest;
- profligate agricultural irrigation, depleting and polluting surface waters; and
- urbanization.

Unsustainable practices in the industries, along with superfires resulting from fire suppression and spread of introduced plants that act as fuel, accelerate watershed erosion, causing excessive sediment loading of channels. In many cases, stresses interact synergistically (e.g., habitat degradation facilitates invasions by alien species, then alien species exacerbate habitat degradation).

After rivers and watersheds have lost the vegetative and geomorphic structures that retained nutrients and sediments, damped hydrologic fluctuations, and provided cover, organisms that retained energy and nutrients and routed them through food webs to higher trophic levels cannot persist in sufficient densities to maintain these services. Eliminating hydrologic fluctuations like scouring floods is not a solution, and in fact makes matters worse. Study of artificially regulated rivers has shown periodic floods to be necessary to maintain habitat (2, 73-74, 90-91), native species (33, 84), and food-web configurations that support fishes and other predators (118, 120-122, 151).

Flow Regulation and Altered Hydrologic Regimes

Artificial, flow-regulating structures (dams, diversions) for agriculture and hydropower and/or flood control have been installed throughout all large rivers and many smaller ones in the West. Only ~70 km of the 2000-km-long Columbia River runs free without the hindrance of dams, which contribute to declines in the region's salmon and steelhead populations to only a few percent of their historic abundance (22, 149). Smaller streams have not escaped. Almost every creek in the Sierra Nevada of CA has been dammed (37). Most of what remains of the CA water system, termed the most massive rearrangement of nature ever attempted (61), is an elaborate network of dams, diversions, canals, and levees where water-discharge regimes are utterly unnatural.

Dams drastically alter thermal, geomorphic, and hydrologic characters of rivers. Thermal impacts on invertebrates have been extensively documented (47, 143-144). Deep (hypolimnetic) release reservoirs cause abnormal winter-warm, summer-cool conditions that disrupt seasonal cues necessary for life cycles of aquatic insects. For example, they may be "fooled" by winter-warm water into emerging as adults into lethally cold winter air temperatures (143). Thermal effects attenuate downstream, but geomorphic impacts (e.g., channel entrenchment when upstream sediment supplies are cut off) extend over much longer reaches, hundreds of kilometers downstream from high dams (150). Direct adverse effects on anadromous fish are well known and reviewed elsewhere (e.g., 22, 103). We focus on how altered flow regimes harm fishes indirectly, through impacts on invertebrates and food webs.

Dams with different purposes distort river discharges in different ways. "Hydropeaking" for electric power generation causes abnormally frequent fluctuations, changing river stage (depth) by meters as often as several times a day. Small fishes and invertebrates are stranded as water lowers suddenly and channels and side pools are drained, then flushed downstream when sudden surges occur (7, 88, 124). Such flows can have direct, lethal effects on invertebrates and young life-stages of fish, and also harm fishes indirectly by diminishing their invertebrate food supply (147).

In contrast, dams built to regulate water supplies for agriculture or flood control reduce natural flow variation, lowering flood peaks and elevating baseflows during low-water periods. Lack of variation also can harm aquatic species, e.g., water birds who nest on sandbars that emerge from the Missouri River during low flows (22). In northern CA, eliminating the high flows that periodically scour river beds degrades food webs that support fish. In Mediterranean climates such as CA, rivers experience bed-scouring floods in winter months and low, decreasing flows during summer drought. Winter floods reset the ecological community, which recovers afterwards as plant and animal populations build back up during the process of "succession" (41). A few weeks or months after flooding, invertebrate grazers are initially dominated by mobile, unarmored species (e.g., mayfly nymphs) that are good fish food. These early successional insects recover quickly after scour and are vulnerable to predators. Over summer, after months of low flow, they are gradually replaced by slower growing, more heavily armored insects (large caddisflies), or sessile larvae (e.g., aquatic moths) that attach to the substrate and live in silk or stone cases. Both are relatively invulnerable to fish and other predators. Consequently, the later successional kinds dominate the "grazers" when flood-free periods are longer than a year, such as during prolonged drought or in channels with artificial regulation (118-119, 122, 151). Preliminary experimental and survey data show lower salmonid growth and densities under flood-free conditions, supporting the inference that floods benefit fishes indirectly through the food web (108, 151).

Another well-documented ecosystem service of flushing flows is the cleansing and resupply of spawning gravels (e.g., 65-66, 73, 101). Natural floods flush fine sediments from stream beds, opening pores in gravels crucial for salmon egg incubation and also as habitat and refuge for invertebrates and young life-stages of fish, including salmon. When reservoirs separate rivers from their natural sediment supply, bed materials are not flushed or renewed. Stream beds become armored or embedded as clean spawning gravels are choked with fine sediments or exported without replacement (66, 73). In addition, flushing flows often suppress invading alien species. Today, many non-native species that threaten natives in western rivers come from still water or sluggishly flowing aquatic habitats (e.g., bullfrogs; 52), largemouth bass and other piscivorous centrarchids (98-99), and mosquitofish (80). These non-native fishes and frogs move into steeper parts of watersheds during low flow, but are displaced downstream to a greater degree than are natives during flood (68, 80).

Alien (Non-native) Species

Of all types of damage to aquatic species and food webs, that most difficult to reverse is the deliberate or inadvertent introduction of non-native species (75). Declines and disappearances of native frogs and toads have been documented all over the West (6, 14, 52, 141), and alien species are an important factor. Introduced predatory fishes have caused amphibian declines in many Western lakes (97, 100). For example, alpine lakes in the high Sierra Nevada were historically fishless until trout, including European brown trout, were stocked, diminishing or extirpating populations of both native invertebrates and amphibians (8, 9, 32, 63-64). Alien bullfrogs, stocked for food in the late 1800s, also threaten native frogs and other biota throughout CA and neighboring states (19, 52, 58, 69). Bullfrog invasion also coincided with declines of aquatic reptiles such as Mexican garter snakes in AZ (128) and western pond turtle hatchlings in OR (83).

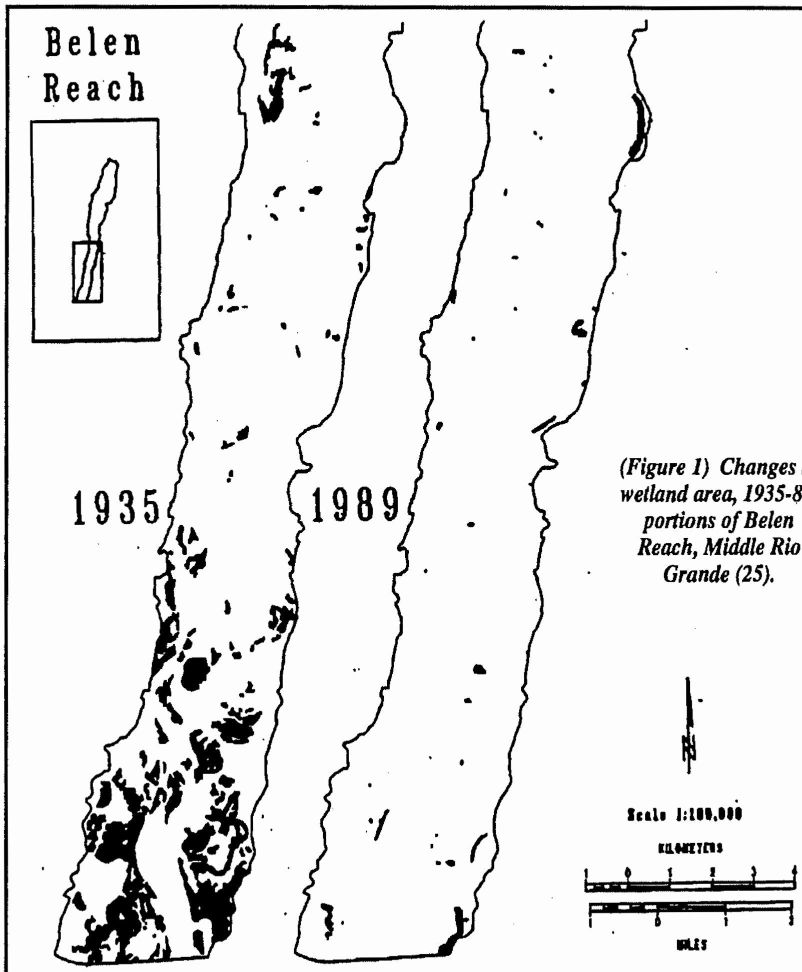
Predatory bullfrogs and introduced crayfish are thought to have been primary causes for Ash Meadows pupfish extinctions in 1950s (149). Because introductions of non-native species co-occurred with habitat loss and hydrologic alterations, their direct impacts are difficult to tease out. Experimental manipulations in large enclosures have nonetheless confirmed that bullfrogs, both as adults (62) and tadpoles (69), decrease growth and survival of native frogs.

Some introductions have caused food webs to collapse with significant, adverse ecological and economic consequences (135). The opossum shrimp was introduced into Flathead Lake and River, MT, between 1968 and 1975 by biologists intending it as forage for kokanee salmon. The salmon supported recreational angling and tourism by bird watchers visiting to see bald eagles feeding on spent carcasses of salmon following their spawning migrations. After shrimp introduction, kokanee declined. The shrimp migrated to great depths by day, so were unavailable as food for the visually feeding kokanee. By night, shrimp moved up to feed heavily on zooplankton, outcompeting young life stages of fish for that resource. With collapse of the salmon, eagles disappeared from their former foraging places along Flathead River and tourism based on fish and eagles withered, with severe economic impacts on local communities (135) (Box 2).

(Box 2) Opossum shrimp were also implicated in degradation of water quality in Lake Tahoe, CA, where its stocking along with exotic trout was followed by periodic decreases and disappearances of native zooplankton, which in turn caused food shortages for fish, and algae to increase (94-95, 125-126). These ecological changes reduced water clarity of the lake, diminishing the aesthetic value of the area and its economic value as a resort and a place to live. After establishment, alien species are difficult or impossible to eradicate. In some cases, however, restoring more natural hydrologic and geomorphic conditions tips competitive dominance back in favor of native species so they persist in more natural parts of the habitat (84).

Loss of Floodplain Habitats

Early accounts by the first European explorers of the Rio Grande Valley in NM described a vastly different ecosystem than today. Historically, the river meandered freely within a 2- to 6-km wide floodplain, alternately destroying and promoting regrowth of riparian cottonwood forests. Floodplain habitats were topographically complex, with numerous sloughs and wetlands. Today, side-to-side migration of the river is constrained by levees throughout nearly the entire 200 km of middle Rio Grande Valley. These levees, along with controlled releases from upstream dams, have disconnected the river from most of its floodplain. A system of drainage ditches and agricultural development eliminated more 90% of the wetlands (25). In 1918, the valley included over 21,060 ha of wetlands, reduced to 3888 ha



(Figure 1) Changes in wetland area, 1935-89, portions of Belen Reach, Middle Rio Grande (25).

by 1935, and to 1620 ha in 1989 (Fig. 1).

Today the dominant invertebrates feeding on detritus in riparian forest along the middle Rio Grande are terrestrial isopods, introduced from Europe. Flood prevention had favored dominance of the forest-floor community by these exotics (33). Spring flooding was reintroduced to a riparian grove not flooded for more than 50 years, which significantly reduced abundance of the introduced isopods while increasing abundance of a native floodplain cricket. These native detritivores are also abundant in the few riparian forests that continue to experience natural, annual flooding. Thus flood control may not only favor exotic plants and fishes (84), but also exotic invertebrates at the expense of natives. Experimental floods also shed light on how control has reduced ecosystem services of both animal and fungal detritivores. After flooding, abundance and activity of fungal decomposers greatly increased in the riparian forest (91). Unflooded sites, in contrast, had greatly reduced decomposition rates, and so accumulated large fuel loads to create substantial fire hazards. In 1996, one of the largest wildfires to date consumed 2430 ha of riparian forest in Bosque del Apache NWR (137). Disconnecting the Rio Grande from its floodplain has shifted the riparian ecosystem from flood-controlled to fire-controlled (89).

(Box 3). Another factor increasing fire frequency and intensity is the invasion throughout the intermountain West of highly flammable European and African grasses (27). Impacts of these grasses on regions like the Great Basin and Sonoran Desert, which had not historically supported continuous carpets of vegetation, are particularly severe. For example, the European annual cheatgrass has spread throughout the Great Basin Desert and increased fire frequency from once every 60-110 years to once every 3-5 years (148).Another European annual, red brome, has spread through the Sonoran Desert and fueled fires which killed the diverse native desert vegetation, including saguaro cacti (26a). More recently, perennial bunchgrasses from Africa are invading from Mexico where they have been planted extensively. The African grasses produce even greater fuel biomass and have quicker postfire recovery, so are likely to fuel even more damaging fires (26b).

Sediment Loading

Fire suppression on forested uplands throughout the West has led to abnormal fuel accumulation. As a result, wildfires are larger and more intense than before, and consequently more damaging to watershed and riparian vegetation. In addition to threats to life and property, abnormally intense fires due to accumulated fuels can greatly increase erosion and sediment yields to streams (Box 3). Increased runoff/erosion following severe fires also may be exacerbated by postfire salvage logging operations. Following most natural wildfires, abundant woody debris remains and riparian vegetation regenerates from surviving rootstocks. Stream/watershed ecosystems thus recover rapidly, in some cases within ~10 years (86). Productivity in intermediate stages of successional recovery (after 10-25 years) may exceed that prior to a fire, perhaps because of terrestrial responses to disturbance analogous to those allowing scouring floods to rejuvenate riverine food webs.

Sediment loading to channels is not only accelerated because of superfires following fire suppression and increased fuel accumulated from introduced grasses, but also by mining, grazing, and timbering practices, in particular from road construction and use in forested lands. Sedimentation from placer gold mining in the Sierra Nevada has been so extensive that surface flow disappeared; stream reaches that were perennial are now seasonally dry (60). Grazing impacts can have similar effects. The John Day River, OR, the longest free-flowing river remaining in the Columbia basin and one of the few salmon-producing rivers in the Northwest still free of hatcheries, is severely degraded by careless cattle grazing, logging, and irrigation diversion that consume 76% of its total discharge (22, 72).

(Box 4) South Fork of Salmon River is within the Idaho Batholith, an area of granitic bedrock with steep topography and highly erodible soils. Logging and road construction begun in 1950, coupled with severe storms in 1962, 1964, and 1965, increased sediment loads by 350% over pre-1950 levels. A moratorium on logging in 1965, with natural recovery and watershed rehabilitation, resulted in substantial improvement (113). That moratorium has since been eliminated.

Degradation of rivers by excessive sedimentation is widespread (Box 4). Sediment release from major clearcutting of the Targhee National Forest, ID, caused decline of a blue-ribbon trout fishery in Henry's Fork of the Snake River. Massive sediment releases were triggered by heavy rains throughout the Pacific Northwest in 1996 as a result of road failures, debris avalanches, and other erosional events.

For more than a century (43, 111-112), streams throughout the West have been strongly influenced by open-range grazing (Box 5), and in arid areas, livestock tends to concentrate near water. Devegetated stream banks contribute silt that fills pore spaces in gravels with fine sediments (24, 145). Such infilling degrades streambed habitat for invertebrates (10, 11, 13, 18, 23, 77, 142). In addition to causing habitat loss and destabilization, fine sediments obstruct respiration, interfere with feeding, and may diminish quality or production of foods (59).

A study of 60 grazed and ungrazed streams in northern Basin and Range and Snake River Plain (127) found grazed habitats substantially degraded, with drastically reduced riparian cover, raw banks, and elevated sediment, water temperatures, and nutrients. Grazed sites also had reduced numbers and diversity of invertebrates that prefer cool water and coarse stony substrates. Stress-tolerant invertebrate species dominated. The base of food webs appeared to shift from terrestrially derived leaf litter, with inconspicuous microbes, to algal production in the channel, with visible accrual of filamentous algae (85). Increased algae in streams exposed by livestock may reflect a number of factors. First, destruction of terrestrial, particularly riparian, vegetation and streambank erosion accelerates nutrient and solar flux beyond levels that a pre-impact food web can absorb. Second, loss of woody debris and sediment choking of stream beds degrade habitat, lowering invertebrate densities thereby diminishing their capacity to remove algae and transfer it up the food chain. Both events suggest that functionally significant food chains that had routed energy to fishes and terrestrial consumers have been weakened and shortened by livestock impacts.

Some Impacts From Mining

Mining operations often yield metals and other pollutants to streams that have clearly detrimental impacts on resident biotas. These can enter from the watershed and be transported in the dissolved state or as sediment (82), and may pass quickly through the system or remain for a variable period of time as sediment, adsorbed to various particles, or accumulated in plant and animal tissues (143). Metals and metaloids may be taken up directly from the water or through ingestion by organisms at various points in food webs, then routed upward to concentrate and sometimes accumulate at higher trophic levels (138). In fact, uptake is often so responsive to these contaminants that analyses of biological material provides an accurate means of monitoring their presence and concentrations (105). Many of these elements and compounds are toxic, and as might be expected, their influences on species and populations are negative (117, 134) so when pollutants are reduced the communities recover at variable rates (17).

(Box 5) Major increases in livestock densities were associated with mining in the 1850s and 1860s, war efforts in the 1910s and 1940s, and with present human population growth (54, 152). Current livestock densities are near an all time high, and grazing policy still represents special interest groups. Grazing is permitted on 91% of Federal lands, which comprises 48% of the total landscape in 11 western states (39). Open-range grazing occurs on 69% of western ranges, covering 260 million ha with about 40% in a state of degradation (112).

Salinization and Pollution From Agriculture

In addition to removing up to 100% of instream flow of rivers (e.g. reaches of the Rio Grande; 22), irrigated agriculture in the arid West also causes unnatural accumulations of salts and metalloids, such as selenium (78), in effluents. Selenium, boron, arsenic, and molybdenum, occurring naturally in soils, are concentrated at unnatural levels in irrigation return flows (21).

The famous case of Kesterson Reservoir, administered by BOR and FWS in the Central Valley of CA, illustrates the threat this poses to aquatic food webs and wildlife depending on them. This large, shallow, saline marsh, consisting of 12 ponds separated by emergent vegetation, was originally designed as part of a drainage system to deliver agricultural return water to the sea via San Francisco Bay. Partially because of concern over potential release of pesticides into the Bay, a drainage system was never completed. In 1972, the marsh became a terminal storage-evaporation-percolation facility, draining 32 km^2 of irrigated farmland.

In 1983, biologists were alarmed by embryonic deaths and deformities in chicks of coots, grebes, stilts, and ducks nesting around Kesterson; 20% of nests had deformed chicks and 40% had dead embryos (106). Selenium toxicity rather than pesticide contamination was identified as the cause of deaths and deformities (21, 55). Selenium was bioaccumulated by organisms of the aquatic food web (Box 6), which comprised species that withstood harsh summer conditions that included partial drying, high salinity and temperature, and low oxygen (55).

Pollution from agrochemical runoff and spraying has also caused plant and animal biodiversity loss in the prairie potholes (45). This area accounts for more than 50% of North American waterfowl production (51). Nesting success appears to have

(Box 6) In Kesterson Reservoir, CA, Primary producers included a large alga, widgeongrass, and smaller algae and other microorganisms that grew on the larger plants; the primary consumers (who fed mostly on smaller algae and other microorganisms) were mostly midge larvae and other larval flies; predatory invertebrates included dragonfly and damselfly larvae and non-native mosquitofish. The top predators were shorebirds, waterfowl, and two species of blackbirds, redwings and tricolored, the latter a candidate for listing as endangered in CA. Managers, under public pressure to act quickly, opted to remove toxic sediments to a disposal site, the most expensive remediation option, which destroyed the tricolored blackbird breeding colony (55-56).

declined, however, at ~0.5% per year from 1935 to 1992 (3). Several possible alternatives were examined, including loss of some wetlands to drainage (139, 146), alteration of hydrologic regime (70) including increased sedimentation, and eutrophication from fertilizer in agricultural runoff (104). None seemed the explanation. Loss of nests to mammalian predators, e.g. red foxes that had increased since settlement, was another possible reason. But nesting success had declined at similar rates where predators were managed (i.e., trapped or fenced) and unmanaged (4). This left agrochemicals, e.g., insecticides already implicated in declines of small predators such as smooth green snakes and pygmy shrews (45), as important in ecosystem changes associated with waterfowl declines.

Most potholes are small (less than 0.4 ha) and dense (up to 40/km^2), with only small margins of wetland vegetation left by cultivation of adjacent row crops. Because they are embedded within agricultural landscapes, it is almost impossible to avoid direct input of aerially sprayed pesticides, even under ideal conditions (51). Direct input comes mostly from over-spray and aerial drift. Experiments showed organophosphates (Box 7) killed mallard ducklings as well as aquatic macroinvertebrates (29); and that organophosphates persisted in wetland soils (30). Management recommendations therefore included farming practices which decrease needs for chemical controls: biological controls and increased buffer zones that are either uncultivated or remain unsprayed when cultivated (28).

(Box 7) Use of pesticides in ND (51, and references cited) increased considerably from the mid-1970s to the mid-1980s (herbicides by 53%, insecticide by 745%, and fungicide by 433%). The most commonly used chemicals were organophosphates (63%), carbamates (15%), and organochlorines (15%). Synthetic pyrethroids which are toxic specifically to invertebrates rather than birds, are also the most expensive options, and were used only 7% of the time. Use of the less toxic alternatives would not protect waterfowl from the indirect impacts of decreased aquatic invertebrate abundance.

Groundwater Extraction/Irrigation: Lowered Water Tables/Salinization

Groundwater mining (pumping that exceeds natural recharge) and diversion of surface waters have both lowered water tables throughout the arid West, threatening intermediate consumers in aquatic food webs and thus the species depending on them. In Mono Lake, CA, brine shrimp and alkali flies were eaten by thousands of waterfowl migrating between North and South America. This highly productive saline lake is a critical "pit stop" for waterfowl on their intercontinental fly-way (92, 140). From 1941 to 1981, diversions to Los Angeles, CA, lowered lake levels by 14 m. Salinity increased towards levels intolerable for both invertebrates, threatening waterfowl food supply. Some waterfowl also were put at risk when lowering water levels threatened to give terrestrial predators access to the island where they nested. Restoration of inflows to Mono Lake in 1993 resolved these threats (93). In many other aquatic ecosystems, however, water allocations remain unresolved.

Another case involving an endangered snail illustrates the value of a species as an ecosystem sentinel. The Bruneau Hot Springs snail is endemic to a complex of thermal springs adjacent to Bruneau River, south of Mountain Home, ID. A major threat to its existence is drastic, ongoing reduction in springflows due to groundwater mining (44). It violates the law in ID to pump more from an aquifer than is replenished by natural recharge, yet local farmers maintain the water is essential to their livelihoods, and withdrawals have produced documented declines in water levels of the springs since 1983. Others, including the Federal government, are concerned that the snail will disappear with the springs, which it will. Because of political controversy over water allocation for habitat vs. farming, the snail has been Federally listed, delisted, then re-listed as endangered. Some local residents recognize, however, that saving the snail might also save the future of farming in the area.

Consequences of Changes: Why We Should be Concerned

Increasingly, people of the USA share the conviction that we should preserve natural biota and landscapes in the West. Intact aquatic ecosystems are obviously crucial to this conservation effort. In addition to ethical or aesthetic motivations, there are strong economic and public health consequences of landuse policy choices that affect the future of western aquatic ecosystems.

Communities that can maintain "healthy" local ecosystems that support fisheries and wildlife will benefit economically from commercial or recreational fisheries, and increasingly from tourism. As states convert from resource extraction to service-based economies, natural ecosystems will enhance the local and regional "quality of life" important to choice of location by future businesses, light industries, and highly trained people. If ongoing landuse practices, like agriculture near Mountain Home, ID, are to be sustained, species like the Hot Springs snail should be conserved as sentinel species whose population trends signal when water extraction is excessive.

Unsustainable timber harvest, grazing, mining or agricultural practices degrade watersheds, causing them to release sediments, nutrients, and sometimes pollutants to rivers or other surface waters too rapidly to be assimilated. Both local and downstream ecosystems are damaged. The unlicensed Cushman Dam, in addition to devastating the salmon and steelhead runs on the North Fork Skokomish River, WA, degraded health of the estuary and once-productive shellfish beds in the Hood Canal (22). Eutrophication of estuaries raises public health concerns, as it can lead to red tides or blooms of other toxic algae (1). Untreated sewage and toxic chemicals discharged into the lower Rio Grande lead to transboundary health problems (hepatitis, diarrheal diseases) between Mexico and the USA. Cholera bacteria persist for long periods on or in marine phytoplankton (20, 34, 36), so eutrophication of estuaries and coastal lagoons takes on even more public health significance. While cholera is not endemic in western USA (Box 8), it is so in the southeast, and was epidemic in temper-
ate South America (Peru) in 1991 when more than 300,000 people were infected and more than 3500 died (46).

In general, there is increasing evidence that human population growth, rapid global mixing of humans and other biota, and environmental disruption are increasing our vulnerability to infectious disease (35, 46, 96). The enormous potential economic and personal costs of this threat further motivate efforts to restore and maintain healthy, sustainable aquatic ecosystems.

(Box 8) New chlorine- and antibiotic-resistant cholera strains have recently evolved (35), further motivating attention to landuse practices and social policies that affect human exposure to the pathogen. One case of the O139 Bengal strain of cholera, which shows alarming virulence and transmission rate, was reported in 1993 in CA, although water-supply sanitation is generally sufficient to prevent it from becoming endemic except at the USA-Mexican border (35). Cryptosporidium and Giardia are protozoan pathogens of immediate concern in the USA, where a 1992 survey showed that nearly 40% of treated drinking water supplies contained one or the other. They are difficult to control because both organisms are resistant to levels of disinfectants used in drinking water, and it takes only a few organisms to produce infection in humans (110).

Issues and Recommendations

ISSUE — Enormous benefits would come from adjusting landuse and development so rivers and streams could once again periodically inundate large portions of their natural floodplains.

Pathogens, pollutants, and excessive nutrients would be filtered by floodplain soils and vegetation and kept out of water supplies. Off-river aquatic habitats would again be available during high flows to nurture fish, bird, and other wildlife populations. Fertility of agricultural lands would be naturally and periodically restored. Flood waters would dissipate over large storage areas before rising to damaging stages.

As this is being written, estimates of damages from the 1997 New Year's flooding in CA alone are climbing from $1 to 2 billion. The costs of damage are a simple function of recently expanded construction on floodplains, as well as the weakening of aging levees. Repair of levees and damaged structures will be followed by future flood damage, which will worsen as development and further attempts to regulate the rivers proceed. A practical alternative has been proposed (71): if building on floodplains is permitted, structures should be on stilts. If function requires structures to be low (as for sewage-treatment plants), they could be surrounded by ring levees. While we are literally in the wake of the 1997 flood, the time is right for State or Federal governments to pursue acquisition of flood-prone lands from willing sellers. But if the opportunity is missed this year, it will certainly arise again in the near future.

• *RECOMMENDATION — Apply purchases, easements, or other means to exclude or regulate certain kinds of development on natural floodplains, with emphasis on restoration and sustainable uses of floodplain/river corridor ecosystems*

ISSUE — Water use in excess of sustainable supplies, salinization of soils and ground water, and pollution, primarily from agrochemicals and mining, are major problems throughout the West.

For example, more river miles (greater than 19,000 km) have been devastated by acid mine pollution than are presently protected by the National Wild and Scenic Rivers Act (22). Many of these problems could be addressed by rethinking social and economic policies and encouraging or rewarding the application of new technologies. Technological methods that could reduce human impacts on aquatic ecosystems are available and await the political climate and economic conditions that will foster their implementation. They are measures that could buy us time as we cope with the more fundamental problem of how to limit human population densities on fragile western landscapes.

• *RECOMMENDATION — Use all available information and technology to reduce impacts and increase sustainability of water resources.*

Examples for which follow:

a) Timber companies should use recently available regional digital elevation models (e.g., 31) to choose areas to cut or not to cut, based on slope stability, proximity to stream channels, and other factors that predict landslides or other risks. Wood should not be undervalued, as it is today in part through Federal subsidies. Value-added industries, in which local residents manufacture products like furniture or musical instruments from the wood they harvest should be fostered. Alternative biomass sources for paper pulp should be sought from rapidly renewing, high cellulose plants (e.g., hemp or Cladophora, a green alga).

b) Application of advanced, available technologies also should be required for agriculture. Retooling to use of drip or trickle micro-irrigation will reduce water needs for crop production and prevent rising salt concentrations in soils (115). Federal water subsidies should be phased out so that crops like cotton and rice are not grown in inappropriate arid landscapes. Several practices may be used to reduce pesticide flux to aquatic surface waters. Conservation tillage, i.e., leaving surface crop residue on the soil as opposed to conventional plow-disk-plant tillage system, would reduce fluxes of biocides borne on sediments. For pesticides originating aerially or in runoff, techniques like subsurface injection are promising. Timing and rate of chemical application are the most important factors which can be manipulated (and regulated) to decrease the magnitude and impact of pesticide fluxes to natural ecosystems (104).

c) Autoclave technologies for metal extraction from ores (132) are presently being implemented at commercially successful mines (e.g., McLaughlin Mine of Homestake Corporation in CA) and can eliminate the risk (or inevitability) of toxic seepage and acid pollution from heap leaching.

ISSUE — The relatively poor knowledge of taxonomy and present (let alone historic) patterns of distribution and abundance in aquatic invertebrates severely limits their use as indicator or sentinel species (37-38).

Aquatic insects do not appear to have suffered high rates of species extinctions as have other aquatic groups, despite the extensive destruction or modification of their habitats (114). This impression, however, could derive in part from ignorance. Our knowledge of distribution, abundance, and change in invertebrate populations, particularly for insects, is limited by lack of taxonomic expertise and lack of past or present survey and inventory data (37), even in National Parks (136).

Another reason for invertebrate monitoring is to assess whether specific restoration and mitigation projects (for example for wetlands) are functioning ecologically, in other words, if functional food webs are establishing. Monitoring of invertebrates will help determine whether newly created habitats can deliver the ecosystem services we desire and require, or are just providing aesthetic value as open space.

We need more and repeated inventories both generally throughout the West and at key sites where environmental trends are monitored. We also need more invertebrate taxonomists. Habitat requirements or trophic roles can differ among species within a genus, even when congeners are difficult to distinguish morphologically.

In some situations, however, simple abundances of three easily distinguished insect orders, mayflies, stoneflies, and caddisflies can serve as useful if coarse indicators for water quality monitoring (40, 142). For example, concentrations of arsenic, cadmium, copper, lead and total metals detected in river invertebrates correlate highly with the abundances of those three groups. Organized volunteers, for example school groups, could be trained to quantify easily recognized and surveyed taxonomic groups, and would make widespread monitoring more extensive and affordable (109).

• RECOMMENDATION —
Emphasize support for training in systematics and taxonomy at both professional and non-professional levels by increasing support for museums, research centers, and general educational facilities. Maintain inventories and data bases on organisms to monitor and detect significant trends or changes in ecosystems, and to test models applied towards predicting future trajectories under various management and ecological scenarios (76).

Conclusions

Organisms at higher trophic levels (e.g., predators) consume organisms at lower levels (e.g., detritivores and grazers) that in turn eat plants, detritus, and microbes, creating a complex web of feeding relationships. All aquatic life is woven into this web, and perturbations created by human intervention disrupt it. These disruptions are reflected throughout the food web, reducing its efficiency at energy retention, cycling, and transport, and ultimately breaking linkages among subsystems which result in ecosystem collapse. Western aquatic habitats have suffered severe impacts from myriad human sources. Although considerable knowledge is available and new techniques exist to ameliorate dangerous situations, their existence is only now being recognized, acknowledged, and applied. Society must move swiftly to assure sustainability of water resources for human use, and even more swiftly if native biotas and naturalness in aquatic systems of the West are to be maintained into the future.

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CHAPTER VI: SUSTAINABILITY OF WESTERN NATIVE FISH RESOURCES

BY

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Introduction

At least 40 kinds of North American freshwater fishes have suffered extinction in the last century (39), more than half this total in arid lands west of the Continental Divide, and 16 since 1964. Moreover, at least 100 additional native western species now are considered threatened, endangered, or of special concern (44). Fewer native species have disappeared from better-watered zones east of the Continental Divide and west of the 100th Meridian (12, 31), but a similar overall pattern exists there.

Major changes in aquatic systems are obvious from this record, which reflects precipitous declines in whole habitats and thus whole communities of unique native organisms. Among the direct impacts are profound, long-term, and continuing changes due to poor watershed practices, followed and augmented by direct and indirect effects of water development. River stabilization and increased numbers, sizes, and impacts of human water-use systems have enhanced introduced, non-native species to the point where their negative influences on natural communities are critical. This paper concerns the preservation of native western American fishes in the face of habitat destruction and in spite of non-native species. Native fishes were targeted not only to emphasize their imperiled status, but just as importantly because:

- Fish and fish communities are sensitive to environmental change, serving as indicators of suitability of aquatic systems for human uses, from drinking water to boating.

- They are widespread in all major aquatic environments of the West and thus appropriate for across-basin and other regional comparisons.

- Their ecology, past and present geographic distributions, and systematics, are better known than is true for any other large group of water-dependent animals (27-28, 32). Changes in numbers and distributions thus may be used to confidently judge both magnitude and extent of environmental change (49).

- Native fishes and fish communities reflect environmental perturbations, are widely distributed, relatively well known, and presently declining, so any successes in recovery are high-profile measures of progress in reversing degradation of physical, chemical, and biological features of aquatic ecosystems.

(Box 1) Of a total of 32 native fishes in the Colorado River basin, for example, 22 (69%) are endemic (found nowhere else in the World); the intermountain Bonneville basin has 20, nine (45%) endemic; and the Sacramento/San Joaquin complex has 13 (33%) endemics of 40 native species. Comparing basin-to-basin isolation, the vast Bonneville and Colorado systems lying side-by-side share only seven species (14% overlap) and more distant drainages differ even more, e.g., only four (6%) in common between the Colorado and Sacramento/San Joaquin basins (45).

Patterns of Diversity

Of 810 native freshwater fishes in North America, 170 (21%) live west of the Rocky Mountains compared with 600 (74%) to the east. Only 40 species (5%) live naturally on both sides of the Continental Divide (44). Evolution of fishes west of the Rockies is rooted in ancient mountain building first isolating them from eastern influence. Continued geologic activity and onset of ever-increasing aridity isolated them even more in separate drainage basins (Box 1). In addition to between-basin differences, natural fragmentation and isolation of habitat by geologic and climatic events resulted in within-basin differentiation of local populations. Thus, genetic biodiversity is far higher than indicated by simple recognition of species. Many of these irreplaceable genetic resources already have been lost due to population extinctions, and others remain unassessed (4).

In contrast to the highly fragmented western fish fauna, that of the eastern slope of the Rockies has 18 native species, none endemic. Farther east on the Great Plains there are about 80 native species (11). Most are spread widely among several watersheds and only 11 are endemic. The last group comprises two subsets, one tolerating harsh conditions of intermittency, high turbidity, temperature fluctuations, and low habitat diversity in smaller streams, and the other adapted to larger systems such as the mainstem Missouri River.

Fish faunas also vary with latitude and altitude. The Pacific Northwest, Sacramento-San Joaquin, intermountain basins, and Rockies in the north all have trouts, salmons, or both, and sculpins. Warm-water groups increasingly dominate at lower elevations and southward, until native trouts are only on mountaintops in AZ and NM, sculpins disappear, and lowlands are inhabited by minnows and suckers. The latter groups are also distributed eastward at lower elevations on the Plains, along with other Mississippi Valley groups like catfishes, sunfishes, and darters.

Introduced species vary considerably in occurrence, with greatest numbers established in the Southwest (41, 48, 50). More than 60 non-native species are in the Colorado basin, nearly twice the 32 natives. Most are from the Mississippi Valley. There are also representatives from the Eastern Seaboard, Great Lakes, Europe, Asia, México, and Central America. The State of California has 51 introduced and 63 native species. In contrast, only 35 introduced species are established in the whole Pacific Northwest (where there are 61 natives); nine in the Great Plains (~80 native); and 12 in the Eastern Rockies (18 native) (11, 33). Most east-slope aliens are trouts. Plains reservoirs harbor warm-water sportfishes and their forage, mostly from elsewhere in the USA.

Problems of Perception: The Value of Non-sport Fishes

(Box 2) -- "American conservation is, I fear, still concerned for the most part with show pieces. We have not yet learned to think in terms of small cogs and wheels (Aldo Leopold, 29)."

A fish of no obvious use to humans (e.g., for food, sport [or both], or some other direct importance) is often considered a "non-resource." Coupled with a lack of recognition of "value" is the fact that most native fishes not eaten or caught for sport are poorly known except to specialists. Even more difficulty lies in the fact that bonds formed between humans and other warm-blooded animals do not trickle down, even to edible fishes and far less so to small, inconspicuous minnows. Perhaps they are too difficult to visualize in their underwater world, too alien to humanize, and too superficially alike for their diversity to be appreciated (Box 2).

A place to start changing such ideas is the premise that native organisms, including fishes, are uniquely adapted to regional/local conditions. Native fishes are positioned at or near the top of the aquatic food chain so when a link is damaged or broken they respond by altering their abundance or distribution, or failing entirely. They therefore provide excellent indicators of total ecosystem "health." Further, their content of scientific information is high. Fishes thus are invaluable for ecological study under field conditions, and ease of propagation makes them excellent laboratory subjects for all aspects of biological research, including biomedical. Their genetics reflect the diversity of events leading to adaptations, and special genetic features of isolated and unique western populations help clarify the process of speciation. There also are aesthetic (fish-watching; simple knowledge of presence; beauty in form, coloration, movement) and ethical considerations, increasingly important to the public, related to native-fish perpetuation (57).

A major policy problem centers around recognition of two categories of freshwater fishes in much of the west: NATIVE SPECIES with long biological histories attuned to the complex geologic and climatic histories; and NONNATIVE (INTRODUCED) SPECIES stocked intentionally by Federal, State, or Local government agencies for sport, forage, pest control, and/or food, or by individuals acting independently for their own recreational or other purposes. Introduced fish populations are frequently enhanced by development of water resources. Conflicts between these two categories and their respective proponents are several, and propose policy questions that must be resolved relative to sustainability of native aquatic life.

Patterns of Environmental Change and Native Fish Responses

Early timbering, plowing of prairies, and livestock grazing altered natural vegetation at the watershed scale, and was soon reflected in major changes from historic discharge, erosion, and sedimentation in streams (Box 3). Flash floods became common due to rapid runoff. Flood power was concentrated downward as water rose against cut banks. Both erosive and sediment-carrying capabilities increased in constrained channels and greater volumes of sediments from eroding hillslopes filled and homogenized bottoms and resulted in dramatically increased turbidity in small-sized to medium-sized streams. Pools became fewer and more transient; intermittency increased. Development concentrated

(Box 3) Before European settlement, runoff flowed slowly from undisturbed watersheds with a larger proportion passing underground. Groundwater filled porous valley soils, assuring more reliable flow. Channels were complex and only locally eroded; pools were common, scoured near boulders and fallen logs; bottoms were of diverse particle sizes; and beaver, common then, added structure through damming and other activities. Riparian vegetation was extensive, from forest to shrub and marshlands. Summer water temperatures were moderate due to shading by plants and in summer/winter alike by extensive ground and surface-water exchange. Damaging floods and droughts were actually less frequent and violent, buffered by vegetated slopes, spongy floodplains, and complex, current-retarding channels. In short, there was more permanent water, habitats were more complex, and extreme conditions were less frequent.

along rivers near travel routes and towns where diversions, dams, and other structures altered patterns and volumes of discharge at the scale of individual streams and began to act as barriers to fish dispersal. Pollution from sawmills, placer and shaft mines, mills and other industries, domestic waste, and agrochemicals, both nutrients and pesticides, became important as human densities and landuse increased. Declines in native fishes were apparent by the early 1950s (36), but most species persisted.

Dam construction (Box 4) had resulted in almost irreversible change by the period 1950-1965, and native fishes began a rapid decline. Western rivers had come under human control of a form that little resembles any natural state, now at the scale of whole river basins. Natural variations in flow were entirely replaced by patterns dictated by downstream water demands. Reservoirs damped upstream conditions, so "headwater" conditions were effectively moved downslope to the outflow from each consecutive dam into the river below. Increased sedimentation upstream was reversed below dams, where rivers were sediment starved since particles were trapped in reservoirs. Channels entrenched as a result, lowering water tables that increased downstream intermittency and desiccation even more. Where surface water persisted, streams formerly passing through braided channels began to flow rapidly through sluiceways over bare gravel and sand, distantly bounded by cutbanks and quickly cooled and heated due to exposure, lower water volumes, and reduced groundwater exchange.

Salinity increased with decreasing discharge variation, end of flooding, increased evaporation from impoundment surfaces, irrigation return-flow, and seepage from agriculture. Selenium, mercury, and other biologically significant materials soon reached unacceptable levels as well. The chemical environment thus deteriorated for fishes as did water quality for other uses. Salinity increases promoted marine fish invasions of the lower parts of some rivers (8), and caused problems as well for treaty obligations between the USA and Mexico in the Colorado and Rio Grande basins, and everywhere for domestic and agricultural water supplies. Pumping, diverted flows, and channel entrenchment dried some habitats, an event fatal for a fish in a few minutes and extirpating whole communities when dams blocked reinvasion when and if flow resumed.

(Box 4) Despite the negative tenor of this report, keep in mind that sustainability is defined in terms of centuries instead of 5- to 20-year "budget" or "authorization" limits. Thus, "Although dams are seemingly permanent features of the....riverine environment, like all artificial structures, they have a finite engineering and economic life expectancy (55)." Planning must include projections for the future after present dams are gone. Public opinion prompting the ACE's "Natural River Option" for the lower Columbia River basin (1), indicates policy changes toward more natural conditions for the near future. If native species are gone the system will be incomplete, so Idaho Rivers United promotes the concept that "Extinction is Not an Option" as part of a campaign to stimulate rethinking for uses of the Snake River system.

After the 1950s and 1960s, even more damage occurred with increased groundwater pumping, mostly for agriculture but also for domestic supplies. Aquifers are depleted through the Plains and elsewhere, resulting in reduced stream volumes and reliability (12). Examples are in the upper Arkansas and Kansas rivers basins, most of the Rio Grande above El Paso, parts of central TX (Box 5), and the lower Gila River basin. Some of these aquifers were filled during long-past times of greater precipitation and are simply not rechargeable under present climatic conditions.

Native fishes were devastated. As rivers were beheaded by dams and natural variation in flow disappeared, so did the resilient species and biological communities adapted to these inherently transient systems. Streams became inhospitable both

(Box 5) Under "right-of-capture" law in TX, an individual or government can legally pump all the groundwater it can "capture," despite damage to subsurface and surface habitats and organisms, or the supply itself (26). The Edwards Aquifer, for example, yields water for ranches, towns, and individuals (a fish-farm allegedly taking an equivalent of 1/3 annual recharge), as well as the burgeoning city of San Antonio. It also supports ~50 endemic, subterranean animals, the richest such assemblage known, including two blind catfish and diverse invertebrates, and surfaces as major springs where more unique fishes and plants live. If San Antonio continues to grow its needs cannot be met without depleting potable water, followed by incursion of unusable water that may require expensive desalinization. All natural surface and subterranean habitats and biotas will be lost. The alternative exists for more reservoirs, with negative consequences for surface waters. Finally, there are possibilities for diversion from elsewhere, with political ramifications and again the need to improve quality through desalinization. No option benefits natural systems; none seems ideal for San Antonio.

above and below high dams. Hydroelectric generators killed fish moving downstream; tailwaters are too cold for warm-adapted species to reproduce. Loss of current or substrate types eliminated those requiring riffles. Reservoirs filled with non-native predators reduced survival of young. Channels directly flooded by reservoirs support few if any native fishes in systems west of the Continental Divide.

In contrast, non-native species flourished as soon as natural flow regimes were suppressed, becoming especially abundant in reservoirs (dedicated fishing lakes also were built) and invading remnant natural habitats. Their numbers and diversity were further enhanced by river control, especially for those less adapted to variable habitats. Hatchery reared fish were also planted in many natural lakes and stream, as a result of actual or perceived public demand for better fishing. As non-native fish diversity and population sizes increased, those of natives declined (50, 52). Increasingly, our waterways became dominated by assemblages of non-native species. Today's most extreme example is in the lowermost Colorado River mainstem, where except for two marine species entering from the sea, the entire native fish fauna is replaced by aliens (40-41). New community configurations develop as non-natives came to dominance, and sometimes even where native species coexist with non-natives. Disturbed ecosystems dominated by organisms that did not co-evolve are inherently unstable as species rise and fall in numbers and new ones invade or are introduced. Such assemblages are far less predictable than native communities, making them harder to manage to favor the species we want, whether sportfish or local endemic (Box 6).

(Box 6) High ecosystem worth of native species is based on the inference that organisms naturally co-occurring are integrated more intimately and efficiently than those brought into artificial contact. Native fishes are long-lived, large-bodied, top consumers in natural aquatic systems. Their feeding on microbes, primary producers (algae, higher plants) and other consumers (aquatic insects, other fishes) captures and stores nutrients in the upper parts of watersheds, foregoing rapid losses downstream where they can contribute to eutrophication of water tables, lakes, and estuaries. In some cases, native fishes are even important in the transfer of nutrients from down- to upstream (e.g., migrating suckers and salmon). Linkages from aquatic to terrestrial habitats also exist (through fish-eating birds, mammals, etc.), as does assistance in control of pests by native fishes feeding directly and extensively on undesirable algae and insects.

Present Conditions

Recovery Efforts. Not much been accomplished in preventing extinction or facilitating recovery of listed fishes. It is estimated that only 4.0% of all federally protected aquatic species with recovery plans have shown significant recovery (68). To our knowledge, none has been downlisted from "endangered" to "threatened" and the only delistings have resulted from species' extinction. Delays in listing because of needed "status surveys," the recent federal moratorium on listing (lifted a few months ago), changes in ways imperiled species are designated as "candidates" for listing, and other hindrances also present problems (Box 7).

The ESA made issues of biodiversity important considerations in allocation and use of resources. Initially, Federal agencies provided leadership to forge compliance. Increasingly, State and Local entities are accepting the need to comply and assuming leadership. Some approaches thus far applied on a large scale (e.g., in whole drainage networks or throughout the ranges of widely distributed species) have been plagued with difficulties that do not differ substantially from those encountered when trying to assure sus-

(Box 7) Endangered species lists have been likened to 'chronicles of extinction,' noting timelags associated with recognized imperilment and resulting backlogs of imperiled forms (e.g., candidates) vs. those listed as endangered/threatened and thus protected by the ESA (59). Funding and staffing are insufficient to meet listing demands, so adequate funding is a top priority for reducing the unprotected backlog. Numbers of aquatic organisms needing protection continue to increase, a trend supporting legislation that protects whole communities before triage is necessary under the ESA (3, 64).

tainability of over-all water resources. Non-human organisms do not recognized political boundaries or land ownership, but humans do, thus major recovery programs are automatically fragmented when rivers flow through multiple jurisdictions. Powerful water interests in the West are agressively protective, and devote far more effort and money to assure current and future resource use and development than to accommodate natural habitats and native fishes (Box 8). The consequence is that commodity values tend to predominate over values that support decisions essential to maintenance of sustainable natural and human communities.

A case in point is the Virgin River basin, managed by or of interest to at least five federal agencies (BLM, BR, FS, FWS, NPS), two or more different regional offices of three of them (BLM, BR, FWS), three states (AZ, NV, UT) with their various agencies, a number of municipalities and irrigation districts, and private landowners, all with prior water rights or claims. The basin in addition to experiencing faster growth in human population than any other part of UT, supports two endangered fishes, another species recently withdrawn from the listing process to allow development of a Conservation Agreement in lieu of listing, and three additional native fishes, plus a number of other aquatic species of concern. Rather than encouraging a multi-shareholder committee structure, FWS supported UT Division of Wildlife as the lead agency. Lower parts of the basin in AZ and NV are thus frequently ignored, actions tend to focus on problems in UT, and funding has become more internalized Direct action by the Virgin River Fishes Recovery Team aimed at preventing native-fish extinction has consisted mostly of attempts to eradicate and exclude red shiner, a highly competitive, non-native baitfish. Local initiatives to development a comprehensive Virgin River Management Plan have replaced the Recovery Team process as the most influential determinant of fish biodiversity (and water-resource use) (Box 9).

An even larger project caught in the web of conflict between resource use and resource conservation mandated by law is the "Recovery Implementation Program for Endangered Fish Species in the Upper Colorado River basin (RIP)," the goal of which is to maintain and protect "self-sustaining populations" of endangered fishes in their "natural habitats." Multi-jurisdictional difficulties are even greater in this much larger region, e.g., the lower Colorado River basin is included in planning for recovery of endangered species, while funding and research/management emphasis is concentrated upstream. The RIP is, however, organized around several large committees with wide representation, an expensive and cumbersome structure that nonetheless gives a broad spectrum of interests a meaningful forum and provides extensive and open review of policies and actions (65). Emphasis has been on instream flow, quantification of which is consistently challenged by water users under State and Interstate water law and compacts.

(Box 8) A recent example was a MOU sponsored by power and water interests and signed in 1995 by the States of AZ, CA, and NV, and DOI. Stated purposes of an "Ecosystem-based Multi-species Habitat Conservation Plan" alternative to Section 7 consultation under the ESA for lower Colorado River listed species were to "accommodate current water diversions and power production and optimize opportunities for future water and power development, while working toward the conservation of habitat and toward the recovery of included species, and reducing the likelihood of additional species listings." This and other aspects of the plan were challenged by NGOs, and wording of the MOU was changed to emphasize habitat and species recovery.

The same scenario of proposal, challenge, and negotiation toward one or the other opposing position (water use/development vs. habitat/species recovery), rather than negotiating toward a common goal of sustainable use, has characterized proposals for fish refugia, population augmentation, management of non-native species, floodplain reclamation, etc. As a result, progress has been disjointed and slow. To date, only preliminary management objectives exist for the fishes, two of four target species continue to decline, prescription of natural habitats needed for recovery remains controversial, and the 15-year program is approaching its 10th year.

(Box 9) In 1980 the FWS issued a jeopardy opinion under the ESA blocking a dam on the Virgin River. Justification for the dam rested on an extensive consulting report (63) funded by the Washingon County Water Conservancy District (WCD), that tended to discount the value of the woundfin, an endangered fish species. Shortly thereafter a chub was listed as endangered and a spinedace was proposed for listing as threatened. The WCD and State of UT then began to assume leadership roles in attempting to integrate biodiversity considerations into water-resource planning. For example, WCD led in developing a Conservation Agreement in lieu of listing the spinedace. The State of UT, responding to the NPS, began serious negotiations leading to a Zion NP Water-rights Agreement signed by DOI, UT, WCD, and Kane County (UT) Water Conservancy District in 1996, which provided for essentially natural flow in the Virgin River through Zion NP and marks the first time UT recognized a Federal water right. UT Division of Wildlife Resources, with cooperation of WCD and other entities, is developing an integrated resource management and recovery program, with a stated goal to recover fishes protected under the ESA. WCD is further trying to develop a management plan to coordinate other agreements, recovery plans, and activities involving water development. This is clearly an effort to implement a comprehensive water-development program while still providing sufficient habitat for endangered fishes. Meanwhile, existing evidence indicates continuing declines in abundance of natives in some parts of the basin under prevailing conditions (21, 24). Thus, the ESA succeeded in lifting biodiversity considerations in the Virgin River basin to prominence, and local leadership responded commendably with basin-wide planning. The several existing documents, however, show a general lack of provisions for corrective action to promote species recovery in the event mitigation plans do not work. The result is that all the initiatives intended to accommodate biodiversity are heavily skewed toward promoting water development. A National policy requiring adaptive management would probably balance considerations of biodiversity and water development more evenly.

Some Positive Trends. Cooperation is greater when fewer organizations and agencies are involved, and some smaller springs, streams, and stream systems have been renovated and their native biotas re-established, although levels of success vary widely. Biologists were able to eradicate a non-native pupfish, thereby saving the endangered Leon Springs pupfish from genetic swamping (25). Removing predatory largemouth bass and other warmwater species from Ash Meadows NWR, NV (62), is ongoing; similar efforts against mosquitofish at San Bernardino NWR, AZ (18), have succeeded in part. Success of efforts to remove hybridizing and competing non-native trout to enhance native golden trout in the high Sierra Nevada, CA are notable, as are some of those for Apache and Gila trouts in AZ and NM and cutthroats in WY, MT, and elsewhere (61). Most of these projects further involve construction of structures that preclude reinvasion of renovated habitats by undesirable species, and in many instances are accompanied by new legislation geared to prevent their transport and reintroduction. It is also significant that some proposed stockings of sport or forage fish into International and Interstate waters have met with strong public and professional opposition (Box 10). Planting new fishes within State boundaries has, however, met with less resistance and complaints are often circumvented. Some new agency actions nonetheless acknowledge past problems of uncontrolled spread of non-natives, albeit in tacit ways. Hybrid northern pike x muskellunge ("tiger muskies") and white x striped bass ("wipers") are "experimentally" planted, for example, on the unconfirmed premise that reduced reproductive (hybrid) capabilities make them more manageable.

There is strong evidence that public opinion is shifting toward a view of greater sustainability. Watershed groups are formed all over the West by concerned citizens trying to find ways to protect their backyards, both for local species of which they are proud and to keep federal regulations at bay. Deer Creek and Mill Creek watershed conservancies, both formed by ranchers, timber companies, and other landowners in northern CA to protect property rights, have been effective in preserving and improving habitat for spring-run chinook salmon and thus associated species. Governor Kitzhaber of OR has made a political committment in his Coastal Salmon Restoration Initiative, focusing in part on establishing watershed groups for coastal streams. A bright spot for coho salmon is Lagunitas Creek, near San Francisco, where numbers have actually increased to become one of the largest runs (~500-1000 fish) remaining in CA because watershed improvements reduced sedimentation and releases from dams provided adequate flows. The weakness and strength of these efforts is that they rely largely on voluntary compliance.

Attention also is being afforded the "naturalization" of other altered habitats, for example by the ACE's "Natural River Option" in the lower Columbia basin, and in Green River by retrofitting Flaming Gorge Dam with variable

(Box 10) One example was in the 1980s, when the State of ND proposed stocking zander, a European relative of native walleye, into waters like Lake Sakakawea, the largest reservoir on the Missouri River, renowned for walleye fishing (9). The native had declined due to water level and temperature variations during spawning and recruitment. Zander were thought more tolerant, better survivors (guarding their young), with a longer spawning period and larger size. There was no evident concern for further losses of walleye from competition, predation, or hybridization. Downstream States were apprehensive, Canada objected strongly, and the Garrison Diversion Project to divert water (and thus likely to transfer non-native fishes) into Hudson Bay drainage from the Missouri and lakes of ND was essentially blocked. "Project Zander" was placed on hold in 1992 with vocal protest from angling groups vowing to keep interest alive.

A proposal in 1989 to establish rainbow smelt in Lake Powell, AZ-UT, as striped bass forage is a second example (22). The introduced bass had depleted its forage (threadfin shad), destroyed trout fisheries, and itself collapsed to population and body sizes deemed unsuitable for a sport fishery. Federal, State, and public resistance succeeded based on certain movement of smelt downstream out of the target area with unknown results, potential negative interactions (predation/competition) with natives and other non-natives, and likely ecosystem-level impacts (e.g., on zooplankton populations).

intakes to promote summer warming of tailwaters to enhance non-native trout growth and native fish reproduction. Operation of Glen Canyon Dam was modified to reduce "tide-like" daily variation in water level of up to 4.0 m created by production of peaking power (7), a change stimulated in part over concern for endangered fishes (6). Changes that will benefit naturalness and native fishes such as decomissioning or removal of dams are further being proposed in the Columbia River system and elsewhere. One of the larger cooperative efforts started in 1994, when CA water users, State, and Federal agencies, and NGOs, signed a Bay-Delta Accord (47), basically a 3-year truce in a battle over water, to try and resolve problems of the Sacramento-San Joaquin estuary. Foremost are two listed species (winter-run chinook salmon, delta smelt) and other declining fish species. Participants attempt to devise projects to satisfy the Accord and keep the truce. The program was fueled recently by passage of Proposition 204, a billion dollar bond issue partially for environmental improvement. Only time will tell if it succeeds.

The emerging trend for Habitat Conservation Plans (HCPs) under the ESA seems to be receiving general support but merits some cautionary discussion. Such plans are negotiated agreements allowing limited "take" of listed species in lieu of Section 7 consultation so long as there is no increased danger to species survival. In reality, they are long-term agreements on land and water use. Developers and other resource users give up something (land for preserves, water for fish, restrictions on land use) in exchange for freedom from concern about protecting endangered species or other organisms beyond the protection agreed upon. The government may invoke the ESA after a HCP is in place, but if this happens landowners, water-rights holders, etc., must be fully compensated for any economic impacts. Thus if a mistake is made and a species becomes even more endangered after the HCP it may go extinct, or saving it is likely to involve large expenditures of public funds. Science-based HCPs are scarce. Most information is provided by owners/developers because agencies are too poorly staffed and funded to do research and independent/historic data are often in short supply. "Adaptive management" that is finding increasing favor with agencies requires managers to learn from mistakes and adapt their strategies accordingly. Under an in-place HCP, some signed for 50 years, change may be difficult. Further, if monitoring is insufficient, success or failure is hard to judge. Some HCPs resemble the old FERC agreements, also signed for 50 years. Only now are many dams up for re-licensing with potential to change operations to benefit fishes. In the meantime, habitats and fishes have been lost.

Introduced Species. Native fishes and fish communities have been actively replaced by non-native species in order to support recreational fisheries. In the past, and not just in the West (5), whole stream systems were poisoned to remove unwanted natives (Box 11). Non-native species were then stocked and

(Box 11) In 1963, Flaming Gorge Dam was closed on Green River, UT. A fishery impossible in the naturally swift, warm, turbid river was soon to be so in a deep, clear, cold reservoir and tailwaters, so State and Federal managers joined to prepare for non-native trout. "Preparation" meant poisoning to deplete or exterminate native fishes and others expected to interfere. In 1962, to the dismay of a vocal few representing the conservation community and a fledgling National ethic, ~700 km of river and tributaries were treated. All kinds of fishes died, including bonytail, Colorado squawfish, humpback chub, and razorback sucker. Detoxification failed, so fish also were killed in Dinosaur NM. Non-native trout were stocked, the sportfishery became legendary, and the natives just noted all are now listed as endangered (22, 37-38).

the stream or lake managed to enhance their numbers (61). Today, except where Federal- or State-listed native species are present (19), such operations still are practiced (Box 12), and even if massive poisonings aimed at native fishes in natural habitats are largely a thing of the past, natives are often managed against or ignored in favor of non-natives. Interestingly, where a new goal in recent years is recovery of species listed under the ESA, non-listed species suffer the same fate. Although exceptions exist (e.g., in CA's golden trout efforts), non-listed native minnows and suckers may not be restocked after removal of non-native trouts (and other species at the same time) for native trout recovery.

(Box 12) The largest fish eradication ever tried was in Strawberry Reservoir, UT. A trout fishery that flourished there failed as non-sportfishes, also mostly non-natives, became common. In 1990, reservoir and tributary treatment with 4.1×10^5 kg of piscicide, followed by 1.5×10^6 cutthroat/rainbow trout and kokanee, all non-native, cost $3.5 million, 75% from the Federal Aid in Sport Fish Restoration Act. Native fishes (none federally listed) were ignored, public support was high, and a sportfishery again exists.

Although many non-native species were deliberately stocked for sport fisheries, others have escaped from commercial aquaculturists. Other sources include dumping of home aquaria and ballast water of ocean-going vessels. Thanks to rapid, modern, and worldwide transportation and poor (or poorly enforced) regulations, such unauthorized introductions are a growing problem contributing to growing conflicts between native and non-native species.

Even when intentional, environmental costs of introduced species often overshadow their projected benefits. Unique and colorful varieties of native cutthroat trout, favored by many anglers, have been eliminated in much of their ranges by competition and predation from non-native trouts. Hybridization between natives and non-native relatives stocked into their habitats, increasingly recognized as a common event, is more insidious, driving populations and species to extinction through genetic swamping (Box 13). Parasites and diseases brought in with non-native trouts have further increased the costs of rearing trout of all kinds, and an Asian tapeworm now infests endangered-species hatcheries as well. Mosquitofish, stocked to control insect pests, have forced native Gila topminnows and other small, native fishes from natural areas where they were better at mosquito control than the non-native. Public health agencies continue planting mosquitofish despite its indictment in the decline and extinction of numerous native species (10, 34). Alien minnows, introduced as bait, also prey on larvae of native fishes making expensive hatchery rearing necessary to prevent their extinction.

Recreational fishing is popular to say the least (Box 14). It is a major industry that depends on the same water resources as native species. Sportfish enthusiasts furthermore concern themselves not only with fishes but also with habitat maintenance, water quality, and other things beneficial to aquatic systems. Yet where major, non-native sportfisheries exist, native species typically do not (41). And, the political reality is that non-native species are the mainstay of recreational fishing promoted by Federal and State agencies and enjoying a large, powerful, and well-funded private lobby (Box 15). Although some NGOs (e.g., Trout Unlimited, Oregon Trout, California Trout) are strong advocates for restoration of native fishes, others are not yet moving that direction.

Conflicts between proponents of native and non-native fishes of the West are more common than often realized. Native-species proposals can elicit an immediate and aggressive rebuttal by sportfishing interests, frequently resulting in quick agency conciliation. If a biologist recommends against a predatory sportfish (e.g., large- or smallmouth bass) through concerns for native species, recreational fishing organizations can mobilize quickly, effectively, and Nationwide against the recommendation, and elicit a National response. The fact that neither bass is native west of the 100th Meridian, certainly not west

(Box 13) Examples of this ever-growing problem include hybridization between native Guadalupe bass and non-native smallmouth bass stocked as sportfish in TX (17), and of native by alien trouts throughout much of the West (2, 60). It is not restricted to sport fishes. Pecos pupfish has largely been replaced by hybridization with sheepshead minnow in TX-NM (16), and pure stocks of two other endangered pupfishes are only protected from similar fates in artificial refugia (20). Genetic evidence for hybridization was found in 25% of individual native and non-native suckers examined from the upper Colorado River basin, to which the non-natives achieved access through interbasin water transfers or as bait (15).

(Box 14) Annually, 50 million anglers generate about $24 billion directly, and total economic output in 1991 was estimated at more than $69 billion, which, in turn, generated $2.1 billion in Federal tax revenues and provided employment for 1.3 million persons (19).

of the Continental Divide, is lost in the heated controversy, considered incidental to the issue, or ignored. Managers responsible for the well-being of native fishes hesitate to alienate interests that wield such formidable political power yet lobby so effectively for clean water and pay part (or influences payment) of the costs for conservation.

Prognosis

The prognosis is bleak for sustaining native fish and fisheries in western waters (41), and has been for some time. Their decline is not a new discovery. It was clearly recognized 50 years ago (14, 35), documented as it progressed (36, 42), and proceeds today (43, 64). Yet many native species are resilient, having resisted extinction over geologic time and through human impacts of the past century as well, and may be expected to rebound if corrections are applied soon enough.

(Box 15) A 10-year, $27 million "Lake Havasu Fisheries Improvement Project" commenced in 1992 by a partnership among Anglers United, AZ Game & Fish Department, and BLM, involves installation of artificial habitats for non-native species, improving angler access, and providing support facilities. Expectations are an increased annual use from 36,000 to 80,000 angler days. At the same time, a $100,000/year BLM/FWS project to maintain native fishes consists of rearing endangered razorback sucker and bonytail in isolation until large enough to avoid non-native predators when stocked into the same lake.

Issues and Recommendations

Success at recovery and maintenance of this unique biota will depend on prompt implementation of actions to address five major issues, the first two dealing in general with aquatic systems upon which the imperiled native fishes depend. The last three deal more specifically with conservation of the native biota. All these issues and recommendations are deeply intertwined with those put forward in other contributions to this report.

ISSUE: Crucial need to recognize degradation of water resources and implement remediation.

Natural Surface waters in western USA, especially those of arid zones, are already seriously degraded in biodiversity, far beyond that indicated by threatened and endangered fishes alone. More than 20 native western fishes have nonetheless become extinct in the past century and 100 more are considered imperiled. Loss of this large a proportion of an entire biota (recall there are only 170 species west of the Rocky Mountains) disallows re-establishing a natural state under any circumstances. Existing and new legislation must therefore be geared at once toward preventing extinction in order to maintain the potential for a natural state and repair of damaged systems. There is ample evidence (43) that native fishes will respond positively to habitat improvement and renovation, thereby experiencing recovery and perpetuation while at the same time acting as indices for assessing progress in habitat and ecosystem rehabilitation.

• *RECOMMENDATION: Formulate and implement policies that insure sustainability of regional aquatic systems and resources, including native fishes and other biota.*

ISSUE: Who pays for western water?

Direct and indirect government subsidies for water developments, holding, and conveyance; mineral extraction; livestock grazing; maintaining sport fisheries, etc., should end in favor of a direct "user pays" principle. Costs of consumptive use would thus be borne by the user by equitable charges for, e.g., acquiring, processing, delivering, and disposing of wastes for critical things like potable and industrial water, or through realistic "royalties" assessed against the real worth of material and products. Such policy would almost certainly result in greater economic constraint for development than exists under current, subsidized systems, and a more controlled pattern of development than exists today.

• *RECOMMENDATION: Apply the principle of "user pays" the true costs of extractive uses of both renewable and non-renewable natural resources.*

ISSUE: Recognition of biodiversity loss and its ultimate impacts.

The situation that biodiversity loss and impaired ecosystem function in western surface waters is in fact critical must be recognized and accepted at the federal and other governmental levels. There is immediate need to reauthorize the ESA in some form, or formulate and pass comparable legislation that supports sustainability of aquatic ecosystems. "Native species" (or "natural habitats") conservation legislation should be considered, where whole communities, habitats, or geographic areas identified as important for preservation of biodiversity or efforts at its restoration are subject to review and potential protection before federal funds are made available or allocated for resource development.

• *RECOMMENDATION: Make available more funding, personnel, and protective legislative to expedite and implement listing or new, alternative forms of conservation to prevent additional losses of endangered species, communities, and ecosystems.*

ISSUE: Realities of the threats of introduced species.

Unlike physical or chemical changes that may be reversed or ameliorated, non-native species, once established, are essentially impossible to eradicate. It thus is reality that introduced species will not go away; they will continue to dominate waterways of the West and must be managed carefully if native species and natural systems are to survive. It should further be recognized that a river swarming with non-native biota is just as unnatural and perhaps more impaired than a polluted, channelized, or impounded stream. Use of the term "natural" must therefore be expanded to embrace not only the physico-chemical features of an aquatic system but also its biology.

The dilemma rooted in prevalence of non-native recreational fisheries in parts of the West, which humans give more importance than native fishes and natural systems, must be recognized and resolved. An increasingly important facet of native fish management hinges on prevention and correction of the pervasive spread and ever-increasing dominance by non-native species. Introduced fishes have clearly become equal to or more important than habitat change as major causes of demise in native western fishes, serving as a final blow that forces native species to extinction or prevents their recovery. A 1996 policy statement by FWS/NMFS (19) deals with some problems associated with conflicts between recreational fisheries and federally listed and species proposed for listing, and speaks to the need for maintenance of natural ecosystems, but does not otherwise deal with non-listed members of aquatic communities. Positive ways to address this situation (30, 56) are:

a) Consistent agency recognition, acceptance, and execution of mandated responsibilities must be strongly encouraged at all levels from the field to upper administration. Some resource managers seriously attempt to comply while others do not. Discretionary action, circumvention or recalcitrance, and in some cases ignoring a situation all can be documented.

b) Native species (e.g., both trouts and warm-water species on the Plains) must be promoted for their sporting qualities and managed in place of non-native fishes. An end to stocking a domesticated, non-native fish in natural waters, when agencies accept the challenge and innovative public education nurtures acceptance, will allow natives to repopulate their original habitats.

c) Another expedient way is to designate and manage altered aquatic habitats exclusively for recreational fishes along with preserving remaining natural systems and restoring others by combinations of:

i) Preventing new introductions through changed agency policies, tougher laws and regulations, and public education. Commercial rainbow trout should continue in use for "put-and-take" and "put-grow-take" fisheries where people can catch them quickly, in roadside streams, urban lakes, and heavily used reservoirs designated for that purpose.

ii) Remaining natural systems should be managed to favor native species' survival and perpetuation, e.g., by maintaining natural flow regimes (46) and setting aside dedicated reserves (51, 67).

iii) Non-natives should be eradicated from isolated streams, springs, and alpine lakes, and from larger systems as needed for native species' survival and recovery, and legislative or physical barriers, or both, should be erected to prevent reinvasions, as is already underway in a limited manner. And,

iv) we need to devise reliable ways or management protocols to keep separate the native and non-native fishes and their habitats (51), and learn more about the ecosystems containing mixtures of natives and non-natives to determine new ways to favor the remaining natives.

• ***RECOMMENDATION: Implement a new kind of ecosystem-oriented management that specifically recognizes and benefits the preservation and conservation of native species, communities, and ecosystems.***

ISSUE: Public education.

"Information and Education" is included as a major category in essentially all recovery plans developed under the ESA, yet remains inadequately pursued. Only a few such programs have been implemented for native fishes. The public remains far less informed than might be expected.

Native species conservation should be integrated with educational programs on clean and abundant water so that fishes can benefit along with water quality and quantity. In the broad view, the melding of knowledge of all stream inhabitants including native fishes with the increasing public appreciation of economic value and aesthetic qualities of riparian vegetation and floodplains, boating, and other water-oriented recreation can only benefit aquatic resources in general. Presenting rivers and other surface waters along with all associated and beneficial geomorphic, chemical, and biological attributes as a single entity should be a major goal.

• ***RECOMMENDATION: Implement ongoing dissemination of information relative to sustainabilty of aquatic resources, from individual species to ecosystems.***

Treat public education as a critical need and primary component of conservation programs rather than as an afterthought.

Conclusions

Recognition that fresh water is a strategic resource that structures natural and cultural landscapes and is a major determinant of regional economics and demographic patterns is mandatory, especially in the arid American West. To protect freshwater ecosystems, we need knowledge, wise leadership, and real cooperation to find the correct mix of laws, incentives, and regulations as well as the political will to enact them (53-54, 58). Native western fishes are clearly disappearing, not just as individual species but up to and including whole communities. As a group they thereby perform a "sentinal" function, reflecting a general deterioration of natural aquatic systems. Reversals of native-fish disappearances will clearly reflect successes of our remediation efforts, if and when we choose to proceed. Ultimately, success will be measured not by the numbers of species saved from extinction, but by how successfully we are able to shift society's values and institutions toward building a sustainable earth (66).

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CHAPTER VII : TOWARD A ROBUST WATER POLICY FOR THE WESTERN USA: A SYNTHESIS OF THE SCIENCE

BY

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INTRODUCTION

Fresh water is a strategic resource essential to human well being. An abundant, easily accessible, and clean water supply is a basic determinant of economies and demographic patterns worldwide (1, 2). However, burgeoning human populations and pollution associated with concentrated activities have so compromised the ability of natural ecosystems to provide humans with abundant, healthful water that scientists are increasingly pessimistic that quality of life can be sustained over the long term anywhere on earth. Indeed, humans have now appropriated for their use about 54% of freshwater runoff that is geographically and temporally available (3). That means that less than half of the global freshwater runoff is available to maintain the natural structure and function of ecosystems that cleanse and purify water so people can use it without contracting disease. Areas of the world where water supplies have been vastly compromised by pollution are characterized by alarming resurgence of waterborne disease and increasing social chaos.

The problem is not confined to foreign nations and the Third World. The USA also has a fresh-water crisis. River flows, except the very largest floods (e.g., Mississippi River, 1993; northern California streams and Red River, 1997) which cannot be contained and used productively, are regulated for human appropriation by hundreds of dams and diversions constructed on all the larger rivers. Ground-water reserves are declining at rapid rates nationwide due to pumping schemes for agriculture and urban supplies. This massive abstraction of water is necessary because about 5,100 liters (1,326 gallons) of water per person per day is used for potable, agricultural, and industrial needs (4). This adds up to a huge volume diverted into human environments, partially consumed and released, sometimes untreated or poorly treated, back into lakes, reservoirs and rivers. Seventy percent comes from surface waters; 23% from ground waters, which are restored (recharged) at rates often less than 0.2% per year by volume.

Most runoff in the USA that is diverted for use is no longer healthful because it is recycled through human systems over and over from headwaters to oceans along river corridors, thereby compromising the natural cleansing capacity of lakes, wetlands, and rivers. We have a crisis because our fresh-water ecosystems both above and below ground are accumulating toxic pollutants, are increasingly acid, saline, or eutrophied (polluted by fertilizers or organic wastes), and increasingly dominated by non-native biota at the expense of native species (2). Urban residents now prefer bottled to tap water and rural residents must drill ever-deeper wells to avoid serious contamination. Moreover, delivery of healthful water to all residents of this Nation now is totally dependent on fossil fuels to provide the energy to store, deliver, and treat water so it can be used safely. Our culture is dominated by a complex economy directly controlled by energy and water markets.

In some ways the water crisis may be more extreme in western USA, which has become the most intensely urbanized area of the country (i.e., a greater proportion of the total population is in cities), because much of the landscape is and people are concentrated around water supplies. Urban expansion and hydropower and agricultural development have virtually exhausted accessible runoff in western rivers; no more economically feasible dam and reservoir sites remain. Many streams and rivers in the and West are substantially dewatered by irrigation diversions and some contain base flows derived entirely from urban runoff and treated waste-water. Pollution is pervasive and often sequestered and magnified (bioaccumulated) by aquatic food webs, even though in most cases dissolved concentrations meet National drinking water standards. Even waters in inaccessible mountains are increasingly loaded with airborne pollutants, if they are not already polluted by human activity directly in their catchments.

MESSAGES FROM THE SYMPOSIUM

The main message for policy makers by papers prepared for this symposium is that freshwater ecosystems in western USA, like most areas of the world, are suffering from myriad human-mediated problems that must be solved by substantially greater investment in conservation and restoration of ecosystem functions. The reality is that we have largely appropriated the available water resources accessible to humans; very little additional water, if any, is available for storage and diversion, at least in reasonable economic context.

In order for economic growth to continue we now need to invest in ways to: 1) reduce per-capita water and energy consumption; 2) improve water-use efficiency; 3) minimize water pollution of all kinds; and 4) restore lost capacity of aquatic ecosystems (the interconnected network of groundwater, lakes, wetlands, streams and rivers) to provide abundant, clean water. The goal should be to use water in a manner that maintains biophysical processes in ground and surface waters in a normative condition that will allow natural cleansing and recycling.

The road to recovery of damaged freshwater ecosystems and confidence in long-term availability of water quality and supply must be paved by a robust water policy. Papers in this symposium provide consensus on the scientific nature and details of how freshwater ecosystems have been damaged. Substantial uncertainty remains about exactly how these ecosystems work and how to accomplish restoration, but a key theme emerged that is essential to a robust water policy: Watersheds are the basic landscape (geographic) units for water resource management.

Water from precipitation flows naturally and inexorably downhill from headwaters on the Continental Divide to oceans through interconnected networks of surface- and ground-water pathways (the geohydraulic continuum). The nature of flow paths is determined by interactions among climate, geology, vegetation, and a legacy of fluvial processes such as glaciation and flooding. Weathering and drainage are primary landscape-forming processes that involve precipitation, water flow, and transport of dissolved and particulate materials within a catchment basin (watershed). Large river basins are composed of smaller interconnected watersheds, each characterized by longitudinal (up- <--> downstream), vertical (surface <--> ground water), and lateral (channel <--> riparian) exchanges of water and materials.

These linkages are critically important because they profoundly influence distribution and abundance of water resources, including aquatic animals and plants, and humans, within a catchment. It is not by chance immigrants focused commerce and development on the aggraded floodplains of watersheds where productivity was high and resources abundant. Most scientists have little difficulty using watersheds to define the basic boundaries of aquatic ecosystems in which natural and cultural processes interact.

Watersheds have been increasingly fragmented and polluted by human activities (5, 6). Reservoirs have inundated fertile floodplains. Flow regulation, irrigation withdrawals, and revetments have uncoupled channel <--> riparian linkages and increased temperature regimes. Deforestation, road building, and cultivation have increased sediment and nutrient loads. Urban and industrial outfalls and diffuse (non-point) sources of pollutants are ubiquitous. All papers included in this symposium spend a lot of space chronicling human influences on aquatic ecosystems in a watershed context. The cumulative effect is unequivocally the loss of ecosystem effectiveness in providing abundant, clean water and associated fish and wildlife resources.

Clearly, a robust water policy to ameliorate pollution and increase efficiency of water use should be stated in a watershed context because natural, cultural, and social processes are driven by the flow of water and materials through catchment basins. This fundamental principle was recognized years ago by John Wesley Powell but then was ignored by the political preserve, stabilize, enhance, and restore aquatic ecosystems to a normative condition. The term "normative" is very important and means that aquatic habitat will be of sufficient quantity and quality to allow maintenance of diverse aquatic food webs dominated by native species that can move between adjacent small watersheds (6). Perhaps "normalization" would suffice as well to describe the goal of sustaining ecological integrity of watersheds while also maximizing use of water resources by humans.

The point simply is that humans need and use water resources and our need for water will increase in the future; but, a balance between use and maintenance of ecosystem integrity must be met in order to insure abundant, clean water for future generations. The papers in this symposium are explicit on what needs to be done. Key management objectives required to establish normative watershed conditions are listed below as synthesized from papers produced by the participating scientists. These should be fundamental scientific principles of a new Western water policy

- **Reduce all pollution sources by developing watershed standards.**

Federal and state laws provide water-quality standards that in many cases do not adequately protect ecosystem processes. For example, drinking-water standards permit levels of dissolved nitrogen of ~5.0 $mg.l^{-1}$, which in most surface waters causes excessive growths of algae. Another example is lack of a sediment standard. Sediments chronically eroded into streams and lakes as a consequence of poor land-use practices (e.g., poorly sited roads) is a pervasive problem that needs addressing by establishing a credible water-quality standard for sediments. Temperature standards also are poorly defined, especially relative to impacts of reservoir discharges on downstream waters and with respect to human influences on stream-side vegetation which moderates water temperatures by shading. It also is important to keep in mind that treated effluents now are primary sources of base flows in arid-land streams. This requires integrated pollution control and perhaps use of constructed wetlands to obtain waters of sufficient quality to allow healthy ecosystem attributes, swimable water, and a food web supporting native fishes to exist.

- **Protect and enhance riparian zones.**

Near-shore wetland (riparian) vegetation and floodplain forests are critically important attributes of watersheds that buffer upland pollution, moderate instream temperatures, and provide woody debris and leaves essential as habitat and food for many aquatic organisms. Wide riparian zones support a rich array of native plants and animals as well as functioning as green belts that add property value, especially in urban environments (e.g., Boise, ID). Controls and incentives for best management practices (BMPs) to prevent over-grazing, excessive logging, road building, and invasions of exotic plants are critically needed in western riparian zones.

- **Recognize that interactions between ground and surface waters are key attributes of watersheds.**

Ground water often is viewed by management and law as never or rarely connected to surface water. However, most aquifers are near the surface and are constantly exchanging with surface waters. Indeed, floodplains and riparian zones are primary areas where groundwater may upwell from alluvial aquifers, producing an array of wetland habitat types. These habitats are crucial for aquatic and riparian biota, including rare and/or migratory species. Moreover, biophysical processes in groundwater flow paths are extremely important in natural detoxification of pollutants. Ground water mining has eliminated interaction zones (river riparia, spring brooks, ciénegas and other wetlands) in many areas of the West and should be discouraged where negative effects are likely.

- **Recognize that rivers need room to roam.**

Floodplains are natural retention devices that help prevent flooding. Human structures should be kept out of floodplains to minimize future economic hardships because legacies of recent floods clearly show we cannot control the big ones. Dams, levees, and other structures not needed, not economically justifiable, or which are clearly compromising biophysical integrity of floodplains and river corridors should be removed.

- **Promote dam operations that create normative discharges and temperatures.**

Seasonal patterns of flow and temperature are vastly compromised by stream regulation, usually reducing instream productivity, extirpating native species, and facilitating invasions of non-natives. Simply establishing minimum flows as mitigation for lost habitat and biota are insufficient to maintain ecological integrity. Periodic flushing flows (bank full or greater) are needed to scour the river bottom and floodplain thereby building gravel bars, digging pools and carrying woody debris into the stream, all of which are critical habitat-forming processes needed by a wide array of aquatic and riparian biota

Flushing flows also can minimize the spread of non-native biota. In addition to provision of periodic flushing flows, it is critically important to reduce the erratic nature of (minimum) baseflows associated with hydropower operations and irrigation withdrawals. Erratic baseflows create a large varial zone along river margins that contain few biota (they are either washed out or desiccated by fluctuating flows). Near-shore, shallow habitat is crucial for juvenile fishes and insects, among other food web attributes that characterize healthy ecosystems. The same concept applies to regulated lakes and reservoirs. River productivity and species diversity can be substantially improved by re-regulation of flow regimes to normalize instream habitats and revitalize riparian and floodplain habitats. Lack of flushing flows and erratic baseflows are perhaps the most pervasive environmental problem for Western rivers (6).

- **Conserve and promote native species by minimizing conditions that allow invasions of non-natives.**

Designation of reserves for remaining suites of native biota and eradication of non-natives where feasible are important components of water policy dealing with recovery of biotic resources. It must be recognized that native biota are sentinels to ecological change. Reductions in their abundance signal the beginning of ecosystem deterioration, and disappearances of sensitive species demonstrates major shifts in an ecosystem that may often precede its collapse. Reregulation of flow and other habitat restoration processes should be used to create new or restored habitats. Restored habitats need to be reconnected in a watershed context by removing physical and pollution barriers to natural migration. Interbasin transfers of water should be evaluated in light of the fact that they compromise flow regimes of source and receiving rivers alike and promote invasions of non-native species.

- **Promote BMPs for upland and riparian land uses.**

DOA has implemented a wide variety of volunteer forestry, grazing, and agricultural practices designed to limit water pollution and loss of biodiversity. Industry also has embraced this concept in many areas. Rigorous, scientific evaluation of BMPs is required, however, before they are universally accepted in place of legal standards.

- **Develop a flexible federalism to allow local watershed councils to bring all stakeholders into the management process.**

A number of recent forums in water resource management (see e.g., Ecological Applications, vol. 6, 1996) clearly have established the needs for interactions among science, management (government), and public/private stakeholders to occur at a local level, in which the watershed is the neighborhood. Watershed (ecosystem) health and integrity is the main goal of these consensus-building processes. Watershed councils or commissions, when properly sized in the context of a key suite of water-resource problems, can be effective in facilitating the necessary dialog involving science and scientists, government, and the various stakeholders (5).

- **Promote subsidies and other actions that foster conservation and restoration of healthy watersheds.**

While watershed councils may often be effective in facilitating dialog and building consensus process, laws that explicitly provide for conservation and restoration through incentives also are essential. The Federal Wild and Scenic River Act and other easement and purchase programs are cornerstones for conservation and protection of aquatic resources. Expanding these efforts is consistent with the broad implications of science to restore ecosystem functions.

Other Federal laws, such as the Clean Water Act, Farm Bill, Safe Drinking Water Act, and Endangered Species Act provide a broad array of incentive programs. The Conservation Reserve Program of the recent farm bills is thought to be successful in reducing sediment and nutrient loading in streams while also promoting biodiversity. The Clean Lakes Program and Total Maximum Daily Load provisions of the Clean Water Act provide watershed approaches to pollution control. But, the benefits of these laws are not widely recognized and understood, especially by local stakeholders, and they argue against the concept that the user should pay for maintenance of water quantity and quality.

Water-rights law in the West seems particularly arcane, given the science clearly shows the need for maintenance of instream flows to restore ecosystem integrity and resilience. For example, allowing interstate water marketing might achieve major ecological objectives for many western rivers while also generating new and badly needed rural income for water-rights holders that no longer have complete consumptive use for their water. The western water edict of "use or lose" is by definition wasteful in the modern world of efficient irrigation systems and promotes loading of pollutants in irrigation return flows. A robust water policy will seek ways to streamline and facilitate provisions of incentives for watershed conservation and restoration already contained in Federal and State statutes.

- **Require rigorous watershed monitoring to allow evaluation of water-management actions and promote basic research to reduce uncertainties in the information base.**

Many billions of dollars are spent annually in the USA storing, distributing, and treating water, and funding management actions that mitigate or compensate loss of ecosystem function or commercially important species (2). Few of these actions are rigorously evaluated in terms of objectives or output. The linkage between science and management, while clearly critical, is in sad shape, particularly in the West. For example, the Bonneville Power Administration has spent nearly $400 million per year for more than a decade to restore salmon runs in the Columbia River. This is in addition to hundreds of millions more spent on compensation hatcheries, bypass facilities, fish screens on irrigation ditches, and pumps and other actions as the massive Columbia River hydrosystem was built. In spite of all this, less than 10 reasonably stable salmon and steelhead runs remain of more than 200 documented historically. Total returns of anadromous salmonids to the river have declined to new lows annually for the last two decades.

By any measure this massive fisheries restoration effort is a failure. Throughout its history the Columbia River Fisheries Restoration Program routinely failed to measure its progress or even base its goals on proven ecological principles. Unfortunately, the Columbia River example does not stand alone. Too many large-scale restoration efforts in the West have been more or less ineffective due to lack of monitoring and evaluation as feedback to the management process.

One success story is the systematic monitoring of river discharge, sediments, temperature, and other variables by GS. These long-term data sets are crucial to future evaluations of water-management actions. Unfortunately, many monitoring sites are being phased out due to lack of funding. It seems that the prevailing paradigm for water-resource management in the West is to try everything and evaluate nothing. New Western water policy must require routine monitoring of biophysical conditions in watersheds as well as independent, scientific evaluation of management actions.

Uncertainty is the bugaboo of water-resources management; there is much we do not know about, how aquatic ecosystems work. Dealing with uncertainty does not mean willy-nilly data gathering or trial-and-error management. Uncertainties are reduced or eliminated in the water resources arena by investment in research. Many eloquent papers have been written urging policy makers to proactively include basic as well as applied research in water-resource management programs; long-term studies greater than five years that effectively differentiate human and natural sources of environmental variation are especially important and logical.

The message has fallen on deaf ears. Far less than a few tenths of a percent of the annual water-resources budget in this country is spent on basic research in aquatic sciences (1, 2). A robust water policy will require significantly greater expenditure on peer-reviewed, scientific research, on the order of 10-20% of annual budgets instead of mere lip service. Clearly, management actions need to be approached adaptively because uncertainties exist and a single prescription likely will be insufficient. But as the papers in this symposium show, aquatic science is sufficiently well developed for management to proceed with proactive, adaptive actions to stabilize, protect, conserve, and enhance the biophysical integrity of watersheds.

The lag-time for technology transfer from science to management can be reduced by fostering meaningful interactions among scientists, managers, and the public using the watershed approach. Western universities should take the lead in research and information transfer but they cannot do it with so little emphasis on research funding. As the colorful U.S. Senator Conrad Burns of MT has put it to me, "We do not have a funding problem in the water resources management arena in the USA, we have a prioritization problem." Most aquatic scientists in the West certainly would concur.

CONCLUSION

Water resources in the West will not be secure without a robust water policy that is based on sound ecological science. Current approaches to pollution control and mitigation of water-development projects are insufficient or inappropriate to maintain a sufficient supply of clean water into the future. We must reduce per-capita consumption of water and energy while also protecting, conserving, enhancing, and restoring the natural integrity of ecosystems (watersheds) that are our source of clean waters. The papers produced by the scientific community for this symposium clearly express not only an empirical basis for the kinds of actions needed, but also a willingness to be proactively involved in the transfer of information to management processes as defined by policy makers.

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APPENDIX:

Scientific names of plants and animals mentioned in text (excluding microorganisms and domestic livestock).

Plants

algae	no scientific name
blue-green algae	Cyanophyta
green algae	Chlorophyta
no common name	Cladophora sp.
no common name	Ulothrix sp.
Alder	Alnus sp.
Aspen	Populus spp.
blue spruce	Picea pungens
cottonwoods	Populus spp.
grasses	Family Poaceae
cheatgrass	Bromus tectorum
red brome	Bromus rubens
saltgrass	Distichlis spp.
hemp	Cannibus sp.
mesquite	Prosopis spp.
Russian olive	Elaeagnus angustifolia
saltcedar	Tamarix ramosissima, and relatives
widgeongrass	Ruppia maritima
willows	Salix spp.

Invertebrates

Aquatic moths	Lepidoptera
Asian tapeworm	Bothriocephalus acheilognathi
Brine shrimp	Artemia salina
Bruneau hotspring snail	Pyrgulopsis bruneauensis
caddisflies	Order Trichoptera
crayfish	Family Astacidae
dragonflies, damselflies	Order Odonata
European isopods	Armadilidium vulgare, Porcelio laevis, P. scaber
floodplain cricket	Gryllus alogus
mayflies	Order Ephemeroptera
opossom shrimp	Mysis relicta
stoneflies	Order Plecoptera
true flies	Order Diptera
alkali (brine) flies	Ephydra spp.
midges	Family Chironomidae, and relatives

Fishes

catfish	Family Ictaluridae
darters	Family Percidae (see perches, below)
freshwater basses	Family Moronidae
striped bass	Morone saxatilis
"wiper"	hybrid, M. saxatilis x M. chrysops (striped x white bass)
livebearers	Family Poeciliidae
mosquitofish	Gambusia affinis
Gila topminnow	Poeciliopsis o. occidentalis
minnows	Family Cyprinidae

Fishes continued

bonytail	Gila elegans
Colorado squawfish	Ptychocheilus lucius
humpback chub	Gila cypha
red shiner	Cyprinella lutrensis
Virgin chub	Gila seminuda
Virgin spinedace	Lepidomeda m. mollispinis
perches	Family Percidae
darters	Etheostoma spp., Percina spp.
walleye	Stizostedion vitreum
zander	S. lucioperca
pikes	Family Esocidae
northern pike	Esox lucius
"tiger muskie"	hybrid, E. masquinongy x E. lucius (muskelunge x northern pike)
poolfish	Family Empetrichyidae
Ash Medows poolfish	Empetrichthys merriami
pupfish	Family Cyprinodontidae
Leon Springs pupfish	C. bovinus
Pecos pupfish	C. pecosensis
sheephead minnow	C. variegatus
sculpins	Family Cottidae
shads and herrings	Family Clupeidae
threadfin shad	Dorosoma petenense
smelts	Family Osmeridae
delta smelt	Hypomesus transpacificus
rainbow smelt	Osmerus mordax
suckers	Family Catostomidae
razorback sucker	Xyrauchen texanus
sunfish	Family Centrarchidae
Guadalupe bass	Micropterus treculi
largemouth bass	M. salmoides
smallmouth bass	M. dolomieui
trouts, salmons	Family Salmonidae
Apache trout	Oncorhynchus apache
brown trout	Salmo trutta
coho salmon	Oncorhynchus kisutch
cutthroat trout	O. clarki
chinook salmon	O. tschawytscha
Gila trout	O. gilae
golden trout	O. aguabonita
kokanee	O. nerka
rainbow trout	O. mykiss
steelhead	O. mykiss (sea run)

Reptiles

Mexican garter snake	Thamnophis eques
smooth green snake	Ophyodrys vernalis
western pond turtle	Clemmys marmorata

Amphibians

frogs	Family Ranidae, Rana spp.
bullfrog	Rana catesbeiana
yellow-legged frog	Rana boylii
toads	Family Bufonidae, Bufo spp.

Birds

coots	Family Rallidae
Bald eagle	Haliaeetus leucocephalus
grebes	Family Podicipedidae
ducks	Family Anatidae
mallard duck	Anas platorhynchus
stilts	Family Recurvirostridae
blackbirds	Family Icteridae
redwing blackbird	Agelaius phoeniceus
tricolored blackbird	A. tricolor

Mammals

American elk	Cervus canadensis
bats	Order Chiroptera
beaver	Castor canadensis
bison	Bison bison
deer	Odocoileus spp.
moose	Alces alces
red fox	Vulpes rufus
pygmy shrew	Sorex nanus