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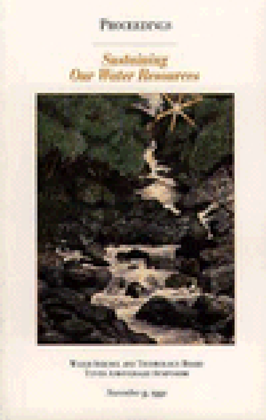

Sustaining Our Water Resources

Water Science and Technology Board, National Research Council

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SUSTAINING OUR WATER RESOURCES

Water Science and Technology Board

Tenth Anniversary Symposium

November 9, 1992

Water Science and Technology Board
Commission on Engineering and Technical Systems
Commission on Geosciences, Environment, and Resources
National Research Council

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"If there is magic on this planet, it is in water."
Loren Eiseley, *in "The Flow of the River," The Immense Journey*

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SUSTAINING OUR WATER RESOURCES

Introductory Remarks

Stephen D. Parker, Director
Water Science and Technology Board
Washington, D.C.

The Water Science and Technology Board (WSTB) staff and I have worked quite hard for 10 years now as agents of the water community at the National Academy of Sciences (NAS)/National Academy of Engineering (NAE), and the National Research Council (NRC). The truth of the matter, however, is that it is an absolute pleasure to be in our position. The success of our program can be attributed to the support and tireless efforts of countless individuals and organizations. Hundreds of the world's experts serve the nation through our network. The federal agencies and their managers and scientists trust us with their thorniest issues, have provided funding in support of our work, and listen to our results. Agencies, universities, industries, and foundations make their people available for service on committees for the good of the nation. The management of the Academies and that of the NRC have been very supportive of the WSTB from the beginning. My staff and I express our appreciation for the opportunity to work with the federal agencies, states, foundations, and industry in the interest of improving decisions and programs concerning the nation's water resources. Sheila David, Jeanne Aquilino, and I have worked together since the board was founded in 1982.

While 10 years seems like a long time, it has passed quickly. I can recall an organizing meeting in early 1982, in the board room of the NAS building, listening to advocates of creative water management, systems analysis, risk assessment, adaptive management, applications of genetic engineering, conjunctive surface and ground water management, water marketing, the role of biology in water science, the importance of wetlands, and the general need for strengthening water sciences and technologies. These then imaginative and innovative topics became **themes** of the WSTB program during the 1980s, as we carried out studies related to water supplies, ice booms, ground water protection and management, clam safety and reservoir management, irrigation drainage, water quality assessments, hydrologic science, erosion policy, and numerous other topics.

As we reflect on our current activities, we have what NAS/NRC Executive Officer Phil Smith calls a "full service board"—that is, an assortment of scientific, technological, and management-oriented activities. Some of this work has come to us easily, but most has required proactivity on the part of the board's members and staff and often courage on the part of someone in the federal government!

As we proceed into the 1990s, I hope we can continue to build on our cumulative experiences and find even better approaches to solving problems and doing our work. I thank the four distinguished individuals who have served as chairs of the WSTB since 1982: Walter Lynn, 1982–1985; John Boland, 1985–1988; Mike Kavanaugh, 1988–1991; and Dan Okun, 1991 to the present. The chairs, board members, and committee members have helped make the program of the Water Science and Technology Board noted and respected, and they deserve much praise for volunteering their time and varied expertise to the board's program.

1

Intergenerational Fairness and Water Resources

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In June 1992, 178 countries met in Rio at the United Nations Conference on Environment and Development to finalize a global strategy for sustainable development[1] that merges environmental conservation with economic development (UNCED, 1992). Sustainable development is inherently intergenerational because it implies that we must use our environment in a way that is compatible with maintaining it for future generations. This intergenerational perspective constrains our management of the environment and its resources, including water.

Water resources are critical to both economic development and the maintenance of natural systems. While water technically does not disappear but only changes form, the quality and quantity of water resources in any one place can be degraded or improved by a variety of human activities. Every generation must therefore be concerned about the supply and quality of water, particularly fresh water, and about who has access to it and at what cost.

We celebrate today the tenth anniversary of the Water Science and Technology Board (WSTB). This is the time frame of half a generation. In reviewing the activities of the board, it is appropriate to put them into the generational time frame and look at their contribution to the goal of achieving intergenerational fairness in the development and use of water resources. In

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[1] The World Commission on Environment and Development, known as the Bruntland Commission, defines sustainable development as a "process of change in which the use of resources, the direction of investments, the orientation of technological developments, and institutional change all enhance the potential to meet human needs both today and tomorrow" (WEED, 1987).

this context it is particularly important that the board has initiated collaborative studies with other countries, for the problem is a global one.

At the WSTB symposium, "Managing Water Resources in the West Under Conditions of Climate Uncertainty", in 1990, I presented a theory of intergenerational equity and its application to water resources. It may be useful here to convey the essence of the theory before examining how the activities of the board during the past 10 years have implicitly advanced intergenerational equity and suggesting how intergenerational concerns can be incorporated in future board activities.

The theory posits that there are two essential relationships—to the natural system and to other generations of the human species. With regard to the first, we are part of the natural system; we are affected by it and our actions affect it. As the most sentient of species, we have a special responsibility to care for the system.

The second relationship is distinctly intergenerational. As members of the human species, we hold the natural environment of our planet in common with all members of our species: past, present, and future generations. As members of the present generation, we hold the earth in trust for future generations and have rights as beneficiaries of the trust to use and benefit from the environment. Past, present, and future generations are partners with each other in the care and use of the planet. Moreover, all generations have an equal normative claim in relation to the natural system of which they are a part. There is no basis for favoring one generation over another in the care and use of the planet.

The concept of intergenerational fairness in using and conserving the planet strikes deep chords in the major cultural and legal traditions of the world, including the Judeo-Christian, Islamic, African customary law, and Asian nontheistic traditions. The notion of equality among generations has deep roots in public international law, as illustrated in the Preamble to the Universal Declaration of Human Rights, the United Nations Charter, the International Covenant on Civil and Political Rights, and other documents (Weiss, 1989).

The intergenerational framework also has an intragenerational dimension. Were it otherwise, members of the present generation could allocate the benefits of the world's resources to some communities and the burdens of caring for it to others and still claim on balance to have satisfied intergenerational fairness. Moreover, poverty today is a primary cause of ecological degradation, which means that maintaining the robustness and integrity of the planet for future generations requires attention to the demands for intragenerational equity today.

When future generations become living generations, they will have certain rights to use the natural system for their welfare and certain obligations to care for it, which they can enforce against one another. These derive from the position of each generation as a member of the partnership of generations across time. In many instances, intergenerational and intragenerational actions are consistent. But in other instances, such as the withdrawal of ground water in excess of recharge rates to supply potable drinking water to poor communities or the rapid withdrawal of water from nonrechargeable aquifers, there will be conflicts between immediate satisfaction of needs and long-term maintenance of the resource. In these cases, means need to be developed to reconcile intergenerational concerns with the demands of the living generation.

PRINCIPLES OF INTERGENERATIONAL EQUITY AND WSTB ACTIVITIES

Weiss (1989) has proposed three principles of intergenerational fairness conservation of options, quality, and access. These are briefly set forth below. The WSTB has gone far toward advancing these principles of intergenerational equity in that it has gathered knowledge essential for assessing intergenerational risks and effects.

The first principle—options—requires each generation to conserve the diversity of the natural (and cultural) resources base, so that it does not unduly restrict the options available to future generations in solving their problems and satisfying their own values. Conversely, each generation is entitled to diversity comparable to that enjoyed by previous generations. Fulfilling this principle can be accomplished not only by conserving resources but also by developing new technologies that create substitutes for existing resources or that exploit and use resources more efficiently. In some instances, maintaining the quality of the resource means enhancing the diversity of the resource base, as in the case of rivers or lakes with rich fisheries or wetlands with their species diversity.

Several WSTB studies have been inherently concerned with this issue. Foremost is that on restoring aquatic ecosystems, including wetlands, rivers, streams, and lakes, once they have been degraded, so that they can be useful to present and future generations. Other studies include those on water transfers as a means to meet the increasing demands for water in the West, on managing water resources under conditions of climate uncertainty, on the operations of the Glen Canyon Dam on the Colorado River, on recharge of ground water aquifers, and on management of the Mexico City aquifer.

The second principle of intergenerational equity is the conservation of quality, which requires that each generation maintain the quality of the planet so that on balance it is passed on in no worse condition than when received and gives each generation a right to planetary quality comparable to that enjoyed by previous generations. While the principles of diversity and quality are connected, they must be treated separately. The analogy is to a trust in which the investments may all be of high quality but not diverse or, conversely, they may be diverse but not of high quality. Both scenarios adversely affect the robustness of the trust.

Many of the WSTB's studies have been concerned with gathering information needed to maintain the quality of water resources. The studies have notably focused on the national irrigation water quality program, contamination of ground water, alternatives for cleaning up ground water, use of ground water models in the regulatory process, managing wastewater in urban coastal areas and the effectiveness of the Great Lakes Water Quality Agreement.

The third principle of intergenerational equity is that each generation should provide its members with equitable rights of access to the legacy of past generations and should conserve this access for future generations. This may be translated, for example, into a right to potable water supplies. The WSTB's studies on providing adequate water supplies of acceptable quality to developing countries advance this principle. These include the studies on the ground water aquifer in Mexico City as a source of drinking water and on soil and water research needed to sustain agriculture in developing countries. The principle of access also means that the present generation must incorporate the full cost of supplying water, not only of delivery and treatment costs, to ensure that the real price of water resources to future generations is not significantly higher than to the present generation. The study of water transfers in the West addresses this issue.

The two binational studies conducted by the WSTB, one with Canada on the Great Lakes Water Quality Agreement and the other with Mexico on the limitations of Mexico City's ground water aquifer as a source of drinking water, both address important intergenerational issues.

In a 1985 WSTB report published by the NRC and the Royal Society of Canada, the committee reviewing the Great Lakes Water Quality Agreement addresses intergenerational equity explicitly in Chapter 7. The study points out that toxic contamination of the lakes represents one of the greatest immediate threats to the interests of future generations because the time necessary to remove them from the lakes through natural processes is very long, especially for Lakes Michigan and Superior. While deterioration in water quality can sometimes be reversed through removal of hazardous contaminants from lake bottoms, rivers and landfills, the costs of doing so may be enormous. In some cases the water quality may become so degraded that future generations will have less flexibility in using it for contact recreation, fishing, and municipal water supplies. The committee recommended that the interests of future generations "be considered more explicitly in the Agreement" and recommended ways to accomplish this (U.S. National Research Council and Royal Society of Canada, 1985).

In its ongoing study of the Mexico City aquifer, another NRC committee is addressing the sustainable use of the aquifer, which is inherently an intergenerational problem. On the one hand, there is a need to supply water for a growing urban population, but there are obstacles to fulfilling this need, such as continued pumping in excess of recharge rates, location of urban settlements over recharge areas, and institutional barriers. On the other hand, there is a problem of water quality in that various pollution sources are contaminating the aquifer. The latter raises the question of how to allocate the costs of preventing and cleaning up water pollution not only across the various strata of society but also across generations. The Mexico aquifer study is also intergenerational in the sense that it addresses the rights of future generations to a potable water supply. It would be useful if the study could address ways in which the interests of future generations in a sustainable supply of fresh water could be integrated into administrative decision making and even into the marketplace.

INTERGENERATIONAL RIGHTS AND OBLIGATIONS AND THEIR IMPLICATIONS FORPOLICY

The principles of intergenerational equity form the basis of intergenerational rights and obligations, which are held by each generation. They derive from the temporal position of each generation in relation to other generations. They are complemented by intragenerational rights and obligations among members of the present generation, which derive from the intergenerational ones. These intergenerational rights are to receive the planet in no worse condition than did the previous generation, to inherit comparable diversity in the natural and cultural resource bases, and to have equitable access to use and benefit from the environmental system. Future generations thus have rights to maintenance of the robustness and integrity of the natural system.

The rights of future generations regarding diversity and quality of freshwater resources represent in the first instance a moral protection of interests, which must be transformed into legal rights and obligations. They are generational rights that exist regardless of the number and identity of the individuals making up each generation, and they can be evaluated by objective criteria and indices applied to the environment from one generation to the next.

Developments outside the environmental area make acceptance of intergenerational rights in the environmental system a natural and desirable evolution. International human rights laws, such as the prohibitions against genocide and racial discrimination, are directed toward protecting future generations as well as the present generation. Eliminating an entire people is legally more odious than murdering an equal number of people who constitute a minority of several groups. Similarly, discrimination denies an "equal place at the starting gate" not only to the present generation of the suppressed group but also by implication to future generations (Weiss, 1990).

The existence of intergenerational rights has significant implications for policy. For example, it may affect population policies, since rapid population increases will affect the demand for resources and strain environmental quality. However, whether a generation chooses to meets its obligations and guarantee the rights of future generations by constraining exploitation, consumption, and waste or by constraining population growth is a decision each generation must make (Weiss, 1993). The rights of future generations mean that the present generation cannot ignore this choice.

Similarly, the decisions we make today about our water resources should be scrutinized from the point of view of their impact on future generations. Scientific knowledge about water systems, identification of the opportunities and limits of technological advances, and understanding of the socioeconomic context in which water resources are used are essential to ensuring fair use for future generations. The WSTB's studies provide a knowledge base, which needs to be extended, for intergenerational scrutiny of decisions affecting water resources.

Intergenerational rights also have significant implications for the marketplace and for the international competitiveness of countries. Future generations are not represented in the marketplace today; they must be. If we develop a market for water, it is important that the rights of future generations to a stable water supply of acceptable quality be incorporated into the market price of water. This requires, first, that we understand the fundamental entitlement among generations. Under the proposed theory, future generations have an equal claim with the present generation to use and benefit from the natural environment. With this as the premise, the task is to develop the appropriate mix of economic instruments to ensure effective representation of future generations (Weiss, 1993). The WSTB studies that look at the use of contingent valuation and extreme values in the context of managing the Glen Canyon Dam and the proposed work on the valuation of ground water offer an opportunity to address the incorporation of intergenerational interests in the marketplace.

Incorporating intergenerational interests is difficult, since the major environmental instruments that we use today start from the point of view of the present generation. The instrument of "externalities" to account for the effects of pollution, such as water pollution, starts from the viewpoint of the present generation. The discount rate, which is the primary tool for considering long-term effects, is ineffective in considering costs and benefits more than a decade or two away (Norgaard, 1991; Rothenberg, 1993). Moreover, with water resources, there are already a number of intentional distortions in the market that are unrelated to generational or environmental concerns. These include the large subsidies to agricultural water and the treatment of water as a resource that has no market price.

Unless we are willing to address the intergenerational dimension of resource use, we will also be unwitting partners in reducing our competitiveness as a country. To the extent that future generations, saddled with much higher levels of debt, have to pay more in real terms for the resources and services they receive today, they will have fewer resources to devote to maintaining options and conserving quality (Kotlikoff, 1992). This in turn will reduce their ability to be innovative in responding to new developments in the market or to new environmental problems.

The challenge before us is to ensure that the interests of future generations in our planet, and our water resources in particular, are represented in the decisions we make today. The work of the Water Science and Technology Board is an invaluable source of scientific knowledge and understanding about how to achieve intergenerational fairness in using and conserving our water resources.

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2

Landscapes, Commodities, and Ecosystems: The Relationship Between Policy and Science for American Rivers

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INTRODUCTION

With the exception of the land from which they flow, America's rivers are the nation's most valuable natural resource. During the mid-twentieth century, the social values that America ascribed to its rivers dramatically changed from an exclusive emphasis on economic development to include preservation. The resulting conflict between development and preservation is mirrored in the scientific investigations of rivers that have supported policy objectives. Previous research founded in reductionist analytic approaches has given way to more holistic investigations rooted in general system theory. The purposes of this paper are to explore the nature of scientific research for rivers against the changing background of cultural values and to examine the interface between science and policy, especially as exemplified by the actions of the Water Science and Technology Board of the National Research Council and the National Academy of Sciences.

RIVERS AS LANDSCAPES

The first intellectual views of American rivers adopted a holistic, interconnected systems perspective. In the early 1800s, when engineers were tinkering with individual river components, geomorphologists were barely beginning to see the interconnections among parts of stream networks, ecologists were enmeshed in species classification, and American artists were depicting rivers as complex landscape systems with physical, biological, and human dimensions (Nygren, 1986). Beginning in the 1820s, painters of the Hudson River School, deriving guidance from the works of Thomas Cole and Frederic Edwin Church, became the first identifiable group of American artists (Driscoll, 1981). They included in their works detailed expressions of the fluvial geomorphology and riparian ecology along New England rivers. For much of the remaining nineteenth century, artists continued this systematic viewpoint rather than singling out particular components for emphasis (Wilmerding and Mahe, 1984). These early painters also provided the first representations of environmental damage from river mismanagement, showing water pollution and forest destruction resulting from reservoir inundation.

The Hudson River School's success continued during the 1830s when Carl Wimer and George Catlin depicted western rivers as complex, interactive mosaics of physical landscapes and biological communities with human significance. Perhaps most remarkable is the record of hundreds of watercolor paintings by Karl Bodmer during his two-year excursion on western American rivers beginning in 1832 (Goetzmann, 1864), with geomorphic features, plant and animal species, and human populations accurately represented as dynamic, interactive systems.

RIVERS AS COMMODITIES

As the nineteenth century progressed, however, the engineering, scientific, and legal professions did not continue this systematic tradition. General American culture has always viewed rivers as simply water, a commodity that could ameliorate an uncertain but potentially productive environment. Anglo-Americans developed a complex set of laws to govern water withdrawals from streams (Trelease, 1979), all founded on the basic precept of river as a water commodity. Major federal initiatives grew out of this commodity-based perspective and became refined into the missions of navigation and flood control by the U.S. Army Corps of Engineers, irrigation development by the Reclamation Service (later the Bureau of Reclamation), and surveying and data collection by the U.S. Geological Survey.

Congress created the U.S. Army Corps of Engineers after the War of 1812 with the expressed purpose of widening the Ohio River channel for barge traffic; the involvement of the Corps in navigation improvement on rivers has continued to the present day (Clarke and McCool, 1985). The Corps' mission was to ensure that rivers would be cheap and efficient conduits for commodity transport, thus justifying a national investment in regional development and economic prosperity. In 1912 the Congress authorized the Corps to undertake flood control projects as site-specific responses to endangered enterprises near rivers (Holmes, 1979). The Corps' activities, emphasizing eastern states because they were the locations of the great flood losses (Figure 2.1). led to the construction and maintenance of thousands of projects that altered river environments throughout the nation.

As the American frontier moved into increasingly arid western areas, it became apparent that agriculture in the new areas would be possible only with federal investment in irrigation projects (Powell, 1878). As the culmination of a broadly based political and economic movement for irrigation development, Congress established the Reclamation Service as a major agency in 1902 (Hays, 1959). Renamed the Bureau of Reclamation in 1923, the agency's mission was to develop large dams and delivery systems to provide water to agricultural producers, a function that limited the bureau's geographical range to western states (Figure 2.2). The Bureau constructed most of the nation's largest dams, and its works impacted every major river in the central and western United States (Figure 2.3).

The manipulation and marketing of rivers as commodities by the Corps of Engineers and Bureau of Reclamation required information about the resource, giving rise to monitoring and investigative activities of the U.S. Geological Survey. The Geological Survey established an internal irrigation survey in 1888 to coordinate the evaluation of potential dam sites and their withdrawal from the public domain, but this politically risky business led to the demise of the irrigation survey and congressional restrictions on the Geological Survey (Stegner, 1953). In the area of water research, the Geological Survey consequently pursued a lower-profile course of stream gaging, mapping, and water quality analysis (Rabbitt, 1980). The Water Resources Division generated significant scientific developments, but as with investigations in all federal water agencies the primary political force behind the research was the management and use of rivers as resource commodities (Graf, 1992).

The combined efforts of the Corps of Engineers and the Bureau of Reclamation together with other agencies and private companies built more than 2 million dams on the nation's rivers; 87 dams impound reservoirs of a million acre feet or more of storage (Table 2.1). The reservoirs are a significant component of the nation's hydrologic cycle because they have the capacity to store an amount of water equal to three years' annual runoff from the nation (Table 2.2). By about 1960 the ethic of river control for beneficial economic development and the associated frenzy of dam construction reached a zenith, and thereafter the number of starts for new structures declined (Figure 2.4). Federal funding for water projects became more difficult to

Figure 2.1 Regional distribution of flood damages in the continental United States, 1902–1937, during a period of emphasis for the flood control efforts of the U.S. Army Corps of Engineers, showing the importance of the eastern states in losses.
Source: Data from U.S. Department of Agriculture, reprinted by permission from Hunt (1974). Copyright ©1974 by W. H. Freeman Company.

Figure 2.2 Regional distribution of irrigated lands in the continental United States, showing the emphasis for reclamation efforts in the western states. Source: Data from U.S. Department of Agriculture, reprinted by permission from Hunt (1974). Copyright ©1974 by W. H. Freeman Company.

Figure 2.3 Distribution of large dams (those with reservoir capacity of 1 million acre feet or more) in the continental United States.
Source: Data from U.S. Department of the Interior (1986), U.S. Department of the Army (1986), van der Leeden et al. (1990).

obtain, all of the best sites had been developed, and the new competing ethic of preservation had grown to formidable proportions.

TABLE 2.1 Census of Dams in the Continental United States

Reservoir Capacity (acre feet)	Number	Total Capacity (acre feet)
>10,000,000	5	121,670,100
1,000,000 – 10,000,000	82	186,480,100
100,000 – 1,000,000	482	136,371,900
50,000 – 100,000	295	20,557,000
25,000 – 50,000	374	13,092,000
5,000 – 25,000	1,411	15,632,000
50 – 5,000[a]	50,000[b]	5,000,000
<50[c]	2,000,000[b]	10,000,000
Total		508,803,100

[a] Mean reservoir size estimated to be 100 acre feet.
[b] U.S. Army Corps of Engineers' estimates.
[c] Mean reservoir size estimated to be 5 acre feet.
SOURCE: U.S. Army Corps of Engineers' data.

RIVERS AS OBJECTS OF PRESERVATION

Preservation of wilderness attributes of landscapes slowly emerged in American culture (Nash, 1973; Oelschlaeger, 1991), almost always in conflict with the prevailing development ethic (Graf, 1990). Beginning in the 1920s, an increasingly organized effort involving resource managers and public user groups pressed for the establishment of formal wilderness areas on federal lands to preserve natural environments. Even after passage of the 1964 Wilderness Act, preservation of river environments was problematical. In the Southwest, for example, proponents of dam and irrigation projects opposed wilderness designations because potential reservoirs might extend into the preserved areas, an arrangement prohibited by the new law (Baker, 1985). Recognizing the special problems in preserving river environments and fresh from political victories that prevented the construction of dams in Dinosaur National Monument and Grand Canyon National Park, the preservation movement secured approval of the Wild and Scenic Rivers Act in 1968 (Tarlock and Tippy, 1970; Goodell, 1978).

TABLE 2.2 Distribution of Water in the Continental United States

Compartment	Volume (km^3)
Ground water	126,000
Freshwater lakes	19,000
Soil moisture	630
Reservoirs	627[a]
Water vapor, atmosphere	190
Ice and glaciers	67
Salt lakes	58
Active rivers	50
Total	146,632

[a] Calculated from Table 2.1.

SOURCE: Federal Council for Science and Technology (1962).

The Wild and Scenic Rivers Act did not give natural objects legal standing in the traditional sense (Stone, 1974), but it lent statutory legitimacy to an alternative to development. The act established a national system that included rivers in varying levels of preservation, and it prohibited dam construction in all river segments included in the system (Coyle, 1988). The dramatic increase in river preservation occurred coincidentally with the dramatic decrease in dam construction (Figure 2.5), partly reflecting the shift in American cultural values placed on rivers. By the time the act appeared, only about 2 percent of the nation's streams remained in undisturbed natural conditions (Echeverria et al., 1989). Engineering structures had coopted many potential wild and scenic rivers, but since 1968 the system has grown sporadically to include 125 reaches totaling almost 10,000 miles of river (Huntington and Echeverria, 1991). The mileage preserved in the system is still a small fraction of the length of river inundated by reservoirs and includes less than one-third of 1 percent of the nation's total natural river courses (Table 2.3). Like the nation's largest dams, the distribution of preserved river segments is heavily weighted toward the West (Figure 2.6).

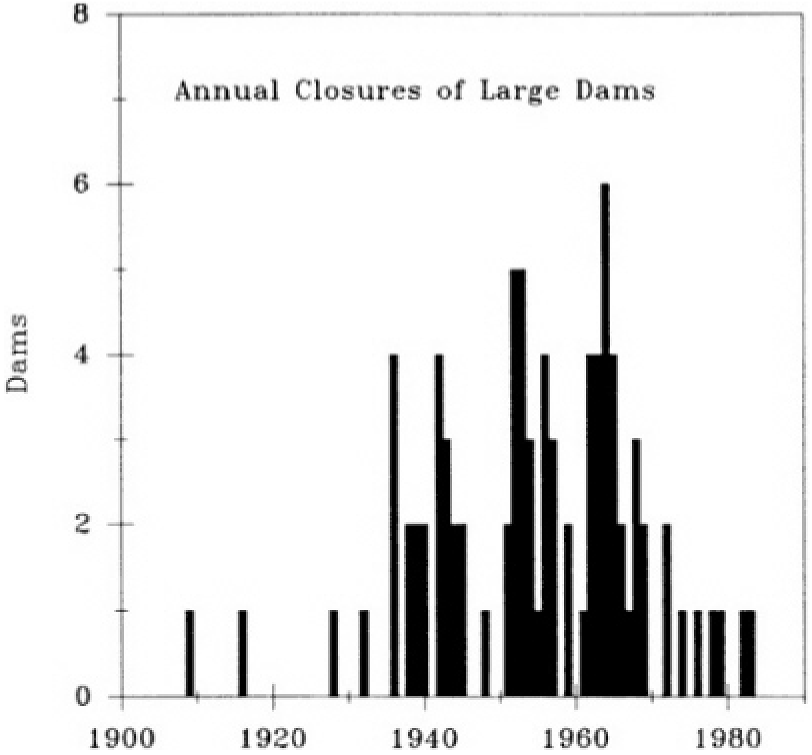

Figure 2.4 Dates of closure for large dams (those with reservoir capacity of 1 million acre feet or more) in the continental United States. Compare with the trends in Figure 2.5.

Source: Data from U.S. Department of the Interior (1986), U.S. Department of the Army (1986), van der Leeden et al. (1990).

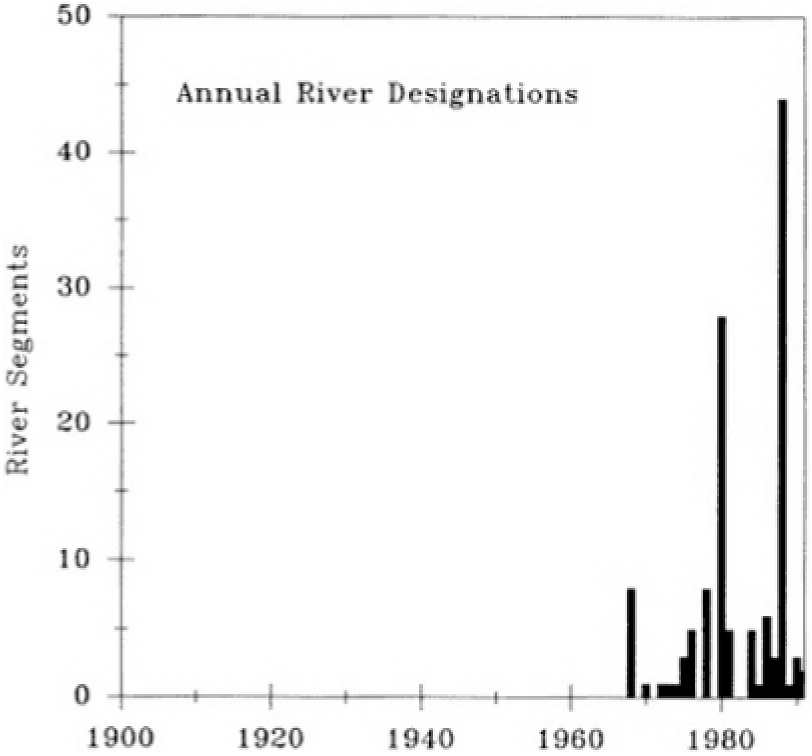

Figure 2.5 Dates of establishment for segments of the Wild and Scenic Rivers System. Compare with the trends in Figure 2.4. Source: Data from American Rivers, Inc. (1990).

The stage for continued conflict between development and preservation is now established on the map of American rivers. Preserved segments and potential candidate segments for preservation are juxtaposed with clams and reservoirs whose operations strongly affect downstream reaches. Unwittingly, the political and economic processes have produced a situation wherein the management objectives of closely associated structures and preserved segments are opposed to each other, but because of strong interconnections in the river systems they cannot be managed in isolation from each other. The constituen cies of all the river resource management agencies have therefore expanded dramatically, and agencies that once competed now must deal with each other with at least a semblance of harmony. These new holistic problems make significant new demands on science for their resolution.

TABLE 2.3 River Mileage in the United States

Status	Miles	Data Source
Total rivers and streams	3,200,000	Echeverria et al. (1989)
Rivers and streams now under reservoir waters	600,000	Echeverria et al. (1989)
Rivers and streams suited for inclusion in the Wild and Scenic Rivers System	64,000	U.S. Department of the Interior (1982)
Rivers and streams included in the Wild and Scenic Rivers System	9,452	American Rivers, Inc. (1990)

SCIENCE FOR RIVER MANAGEMENT

Scientific investigations of American rivers have always been the handmaidens of public policy for riverine resources. Geomorphology developed as a distinct science within geology and geography at the close of the nineteenth century (Chorley et al., 1964), and the first hydrology textbook appeared in 1904 (Chow, 1964). The emergence of these sciences coincided with the burgeoning interest in water resource development early in the twentieth century, when scientific investigations of river processes were usually related to assisting in the solution of engineering problems. Gaging and analysis of western river discharges, for example, were largely in support of the search for suitable rivers and sites for the construction of large federal clams (see, e.g., LaRue, 1925). Investigations into the hydrologic and geomorphic impacts of various land use practices resulted from efforts to understand and control erosion and sedimentation that threatened water resource development (see, e.g., Thornthwaite et al., 1942). When these early scientists and associated engineers (such as Frederick H. Newell, an early director of the Reclamation Service) became part of the administering bureaucracy, they brought their engineering and science with them. They were administrators

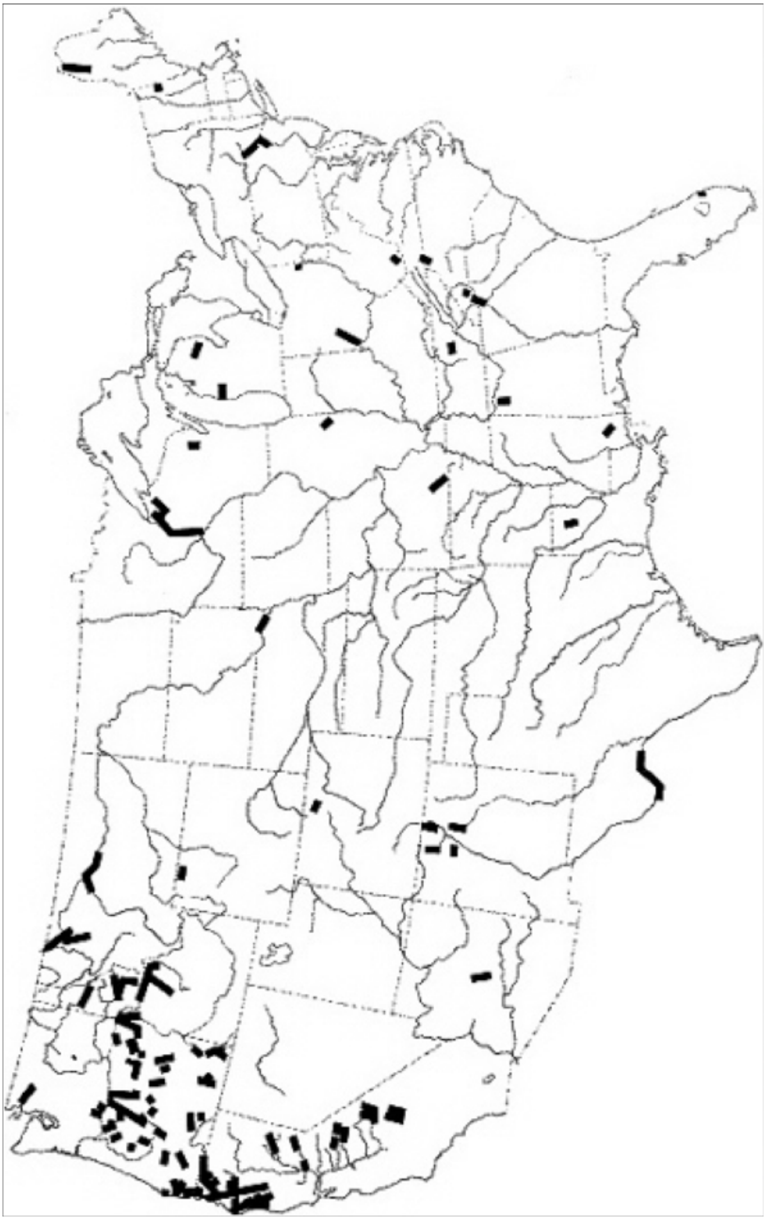

Figure 2.6 Distribution of units of the Wild and Science Rivers Systems in the continental United States. Source: 2.6 Data from U.S. Forest Service (1991).

who "had little faith in democracy as a social remedy.... [T]hey expected society to be saved by a technical elite" (Layton, 1971).

Because of the strong association between science and engineering for rivers, much of the science of the first half of the twentieth century was a reductionist, analytic approach closely related to engineering principles (reviewed by Leopold et al., 1964, who also showed an interest in systems). By dissecting the river into its various components and explaining their individual workings, the analytic approach vastly improved understanding and prediction of the behavior of natural streams. It also directly supported structural engineering efforts to exert control over river behavior because structural approaches tended to address particular limited aspects of rivers, such as controlling discharge, stabilizing banks, or deepening channels. By the late 1950s the Water Resources Division of the U.S. Geological Survey was developing sophisticated theory as well as addressing particular problems using an analytic approach (Tinkler, 1985).

In the mid-twentieth century, while the public ethic for river management began to shift from strictly economic development to a more complex view that included preservation, river sciences also began to undergo a change in perspective. The analytic approach continued as a successful and forceful paradigm, but it faced increasing competition from a general systems perspective. This approach considered the river as a complex collection of interacting elements and emphasized investigation of system-wide behavior, a perspective that fit comfortably with the emerging environmental perspective considering multiple uses of multiple resources associated with the river landscape. The systems viewpoint had been present in geomorphology and hydrology from their formative years (Thorn, 1988), but it was not especially prominent in process research. Gilbert's (1877) classic Henry Mountains work, often cited as the first major statement of fundamental geomorphologic principles, has a distinct systems perspective on fluvial processes. Later, in the New Deal Era, federal hydrologists developed water budget models for river basins that were essentially systems for economic planning (Blaney et al., 1937). The analytic approach, however, dominated geomorphic and hydrologic work well into the twentieth century.

Wide application of the systems view emerged mostly from the life sciences and was associated with the twentieth-century version of the science of ecology, which, despite a long gestation period, did not become prominent until the 1950s. Life scientists have tended to adopt the term ecosystem, proposed by Tansley (1946), as the entire complex of organic and inorganic components interacting with each other in a biome and its habitat. Geomorphologists and hydrologists did not widely adopt the systems perspective until yon Bertalanffy (1950, 1962) published a broad general systems theory that included a calculus and terminology. Rather than assessing variation in individual measures of river behavior, recent research has assessed river system behavior as responses in several variables interacting with each other and with physical, chemical, biological, and human-manipulated controls (Chorley et al., 1984; Graf, 1988).

THE SCIENCE-POLICY CONNECTION FOR RIVERS

The mutually influential relationship between science and policy has operated for both the development and preservation ethics. The analytic investigations of sediment transport, hydraulic behavior of flow in natural channels, and the responses of flow to various artificial structures (reviewed by Chow, 1959) had clear connections for efforts in dam, levee, canal, and channel construction. Alternatively, systems science had an equally important connection to the preservation view of society and nature (Glacken, 1967). The work of the German geographer Alexander yon Humbolt led directly to environmental systems interpretations by British naturalists whose proselytizing spurred colonial laws preserving forest and range ecosystems as early as the 1850s and 1860s (Grove, 1992). Preservation of riparian ecosystems in the United States did not occur until 100 years later.

General systems approaches, whether explicitly stated or simply inherent in research designs, have important implications for potential policy applications, because such approaches tend to emphasize the multivariate aspects of environmental systems. Causal relationships are rarely seen as simple connections susceptible to easy structural management, and changes intentionally introduced to the system at one place are usually seen as having far-reaching consequences elsewhere. In its new guise in the late 1900s, the river-related research of geomorphology, hydrology, and ecology was therefore more likely than ever before to support system-wide management and operations solutions to problems and less likely to support geographically limited structural solutions.

Systems science has been slow to affect federal agency research for rivers. The managers of large federal river projects now deal with complex interactive systems, and even though systematic planning for economic purposes is common (as in the Tennessee Valley Authority and western regional hydropower administrations), scientific research in agencies has not often adopted similarly broad perspectives. Analysis of details instead of system behavior continues to be the primary source of information for decision makers dealing with structural management and impact analysis, in part because of continued emphasis on technology and (by implication) engineering solutions.

Scientific input, whether analytic or systematic, is a major component of public policy decisions affecting rivers. The American public, through its elected representatives, continues to support the infusion of scientific opinion into decision processes, and critical editorial comment is sure to follow any major river management decision that does not appear to have the patina of scientific validity. Decision makers themselves often demand scientific input, and the operating rules of resource management agencies dealing with rivers frequently include the provision that management practices be "scientifically sound" (as in the case of contaminated sediment management by the Environmental Protection Agency; EPA, 1992). In many instances, the law includes scientific input to decisions, either in the adjudication of disputes with the testimony of expert witnesses or in decisions that direct an agency to pursue practices that are scientifically valid (as in court decisions affecting the Bureau of Reclamation; NRC, 1987).

Scientists themselves are less enthusiastic about participating in research that has public policy implications or that might stir political debate. River scientists who entered the field during the 1960s and 1970s frequently are unwilling to enter difficult and contentious arenas that might jeopardize their funding sources, and geomorphologists and hydrologists often avoid research topics with sharply defined political implications. Ecologists seem more likely to engage in such work, but scientists in all three fields tend to be widely dispersed in universities and government agencies, so that the development of a critical mass of researchers who might influence policy is difficult.

Despite these reservations, some scientists do work directly with policy makers, and there are certain common themes evident in those situations where science and policy have worked well together. The probability of successful interaction is highest if policy formulation and funding for research are simultaneous. For example, in river engineering cases, simultaneously planned and funded geomorphologic and engineering studies have been effective in creating near-natural and stable environments (Coates, 1976). Success has also been common in those cases where university researchers interested in basic science have teamed with management agencies seeking an intellectual framework for applied problem solving. Schumm's (1977) redefinition of general systems approaches for rivers as an outgrowth of the needs of river management agencies such as the Corps of Engineers is an example. Finally, success has occurred where a critical mass of researchers and resources has been achieved, such as in the experimental watersheds and research staffs of the Agricultural Research Service focused on forest and range management issues (e.g., Alonso, 1980).

Those cases where science and policy have failed to interact effectively fall into five general categories (modified from Chelimsky, 1991). First, there are some issues that can be decided only in the political arena, irrespective of any scientific evidence that might be produced. The ongoing debate over the definition of federally protected wetlands may be an issue of this type. The scientific validity of any accepted definition appears to be less important than the resulting geography of wetlands. Second, science clearly does not work well in a policy support role where research requirements exceed available resources. For example, although the United States has maintained the world's most extensive stream gage network, many policy decisions require even more data on water quality and sediment, the collection of which is prohibitively expensive. As a result, decisions must be made with considerable uncertainty and must rely on estimates rather than firm empirical data. Third, some policy decisions ask questions that are at the cutting edge of present day science. Problems associated with irrigation drainage and selenium pollution in the San Joaquin Delta illustrate a matter where adequate understanding was simply unavailable early in the management process (NRC, 1989).

Two additional types of problems involving the science-policy connection may lead to erroneous results: advocacy science and entrepreneurial science. Advocacy science occurs when an interest group or management agency sponsors in-house research with the direct intention of controlling the outcome of the work for political purposes. Researchers in this arrangement may feel obligated to report results supportive of the position of their sponsor. Finally, some researchers pursue their work solely for monetary reward, an acceptable practice as long as the pursuit of contracts does not produce results tailored for sale.

AN INTERMEDIARY BETWEEN SCIENCE AND POLICY

The Water Science and Technology Board of the National Research Council and National Academy of Sciences has played a unique and critical role in improving the science-policy connection. Since its founding in 1982, the board has produced more than 20 independent reviews and studies that concentrate on establishing a productive science-policy interface. Most of these efforts have performed oversight functions, assessed the scientific needs of policy makers, or searched out directions for future research.

The board has acted as a sort of intellectual umpire in cases where the issue is the assurance of the quality of science being used by public agencies. For example, when the Army Corps of Engineers undertook a massive analysis of the water supply for Washington, D.C., Congress mandated oversight of the scientific and technical aspects of the work by an independent group (NRC, 1984). Other oversight efforts by the board included advisory work for the Geological Survey in the development of its National Water Quality Assessment Program (NRC, 1990) and its Water Resources Division (NRC, 1991a). In what will probably become the longest-running oversight effort of the board, one of its committees continues to advise the Bureau of Reclamation in its research to assess the effects of Glen Canyon Dam on resources downstream on the Colorado River in Grand Canyon National Park (NRC, 1987, 1991a).

The board has also attempted to better define the scientific needs of policy makers. In two major studies on the safety of dams, committees of the board assessed the state of knowledge for dam safety and identified reasonable criteria for decisions in support of structural management (National Research Council, 1983, 1985), leading to national legislation. In a sweeping review of irrigation drainage problems, a committee of the board used the San Joaquin Delta experience as an object lesson on project management (NRC, 1989).

The board has assumed a leadership role in defining developmental needs to ensure that science produces useful explanation and direction for policy. Examples include assessments of the general hydrologic sciences and the emerging subfield of aquatic restoration (NRC, 1991b, 1992). The board has stressed the need for empirical science to support technological advances in hydrologic engineering. One outgrowth of the effort has been the establishment of the Hydrological Sciences Program of the National Science Foundation.

There are several common themes that arise from the board's experience in working at the science-policy interface (Leopold, 1990, identified some of these themes from a general perspective). In most oversight cases, for example, political or legal pressures forced the public agencies to become reluctant bedfellows with the board. In a Washington area water supply study, for example, Congress required that the Corps seek independent review, and in the Glen Canyon Dam issue court-mandated requirements for scientific validity drove the process for the Bureau of Reclamation. Once involved with the board, agencies have at first systematically resisted board suggestions for improvement of their scientific activities, but in many cases the agencies later relented after contests of will and endurance.

The board has also repeatedly espoused several common intellectual themes in reports to agencies. Calls for general systems perspectives have been frequent as the board has attempted to persuade agencies to conduct their research in a broader, systematic fashion better suited to their complex mandates than the more traditional analytic approach (Figure 2.7). Application of the systems perspective is related to the common board admonition to

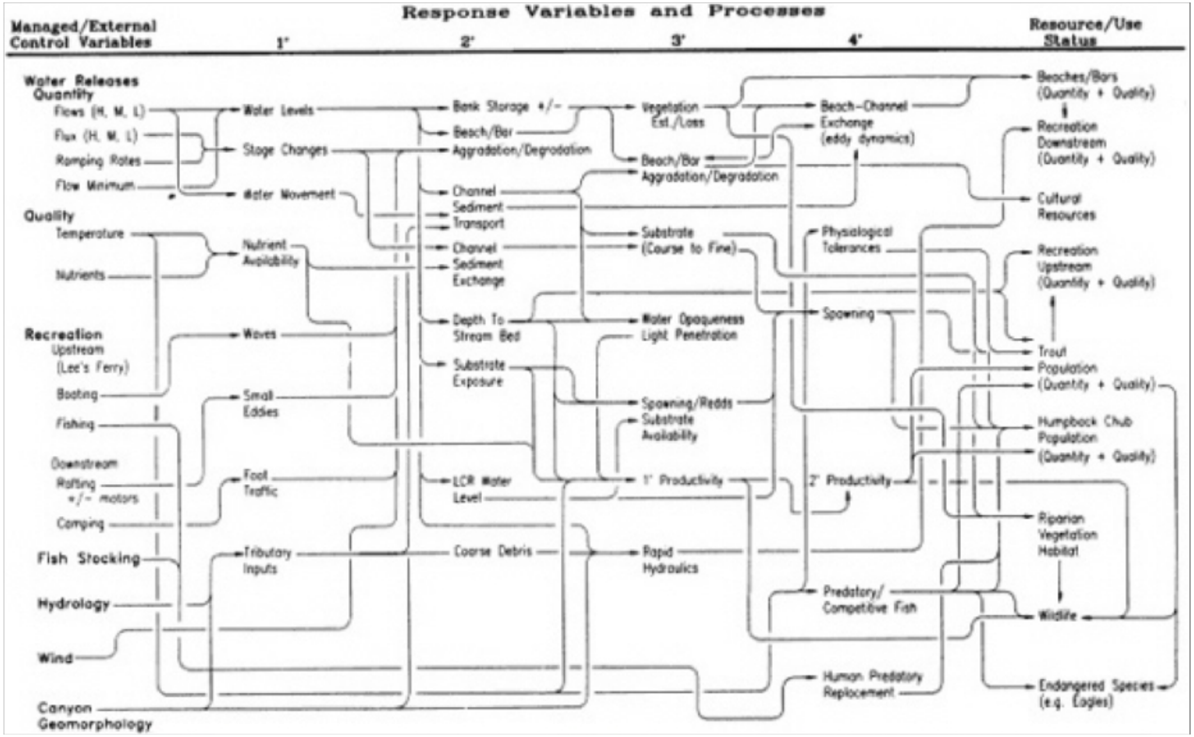

Figure 2.7 An example of a general system perspective that originated in discussions of a committee of the Water Science and Technology Board, informally referred to by users as "The Spaghetti Diagram." The system was designed h by D. T. Patten to guide Bureau of Reclamation research on downstream impacts of the operations of Glen Canyon Dam.

devote more attention to environmental impacts, especially those that extend beyond the immediate project area and beyond the physical environment to social and cultural aspects. Although most members of the board and its committees are scientists or engineers, most major reports call for increased population by social scientists to reflect these extended concerns.

The board also has repeatedly identified the same issues related to the management of science. Often, agency research lacks clearly defined statements of the research questions, so resources are invested in dealing with nebulous issues rather than specific research problems. The board has also noted a consistent lack of cooperation among related federal agencies, an endemic disease wherein each organ of the government experiences bureaucratic tissue rejection when dealing with other agency organs, even when common interests are obvious. Finally, the board has noted in several reports that there is a need to pay more attention to research as opposed to mere data collection. Environmental monitoring and surveillance are not enough to be effective supporters of policy —they must be accompanied by insightful interpretation and analysis.

CONCLUSIONS

From the earliest intellectual attempts to understand American rivers by landscape painters to the most recent systems representations, the objective has been to create a vision of what these resources are and what they should become. The present uncertainty about the future of rivers and the fragmented management structure are not unique. Similar chaotic conditions characterized the nation's policy for public land in the past. In response, at several times the nation established public land law review commissions to create visions of public land resources (e.g., Public Land Law Review Commission, 1970). It is now time to establish a public river policy commission to establish a national perspective on our rivers, a perspective that is larger than individual resources, agencies, or agendas. Such a commission would involve representatives of resource users, management agencies, public interest groups, and researchers. The commission would strive for agreement on a federal strategy for truly integrated and systematic river management that is a finely defined balance between commodity development of individual resources and preservation of selected river landscapes.

There are two primary reasons for developing an integrated approach to river management that avoids the present fragmented management approach. First, it is necessary for the nation to protect its immense investment in river management infrastructure ($16 billion for the Bureau of Reclamation alone) from unwise and poorly thought-out attempts at environmental protection. The structural investment in American rivers has contributed immeasurably to the evolution of the United States into the most wealthy and powerful nation in the world. To manage the structural investment for continuing sound economic return for future generations is a logical progression from the recent period of construction.

Second, the remaining 2 percent of the nation's rivers that are undeveloped should remain so, with a management strategy that protects their natural conditions from damage by the operation of nearby river reaches dedicated to commodity-based use. The protected river reaches offer individuals and small groups the opportunity for recreation of the highest sort, the opportunity to recreate (albeit briefly and somewhat artificially) the frontier experience. This experience, emphasizing self-reliance and independence, shaped a nation and its people. It is therefore worth preserving, even at great cost.

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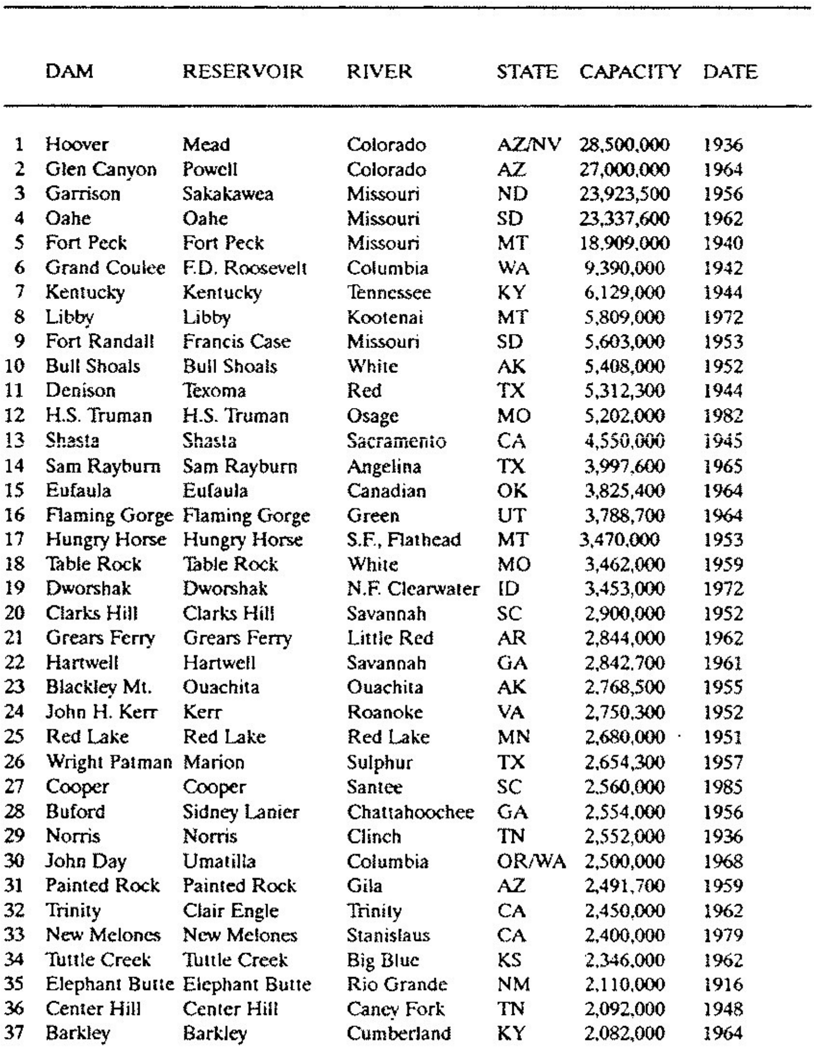
APPENDIX 2A

The following table identifies dams in the continental United States with reservoir capacity of 1 million acre feet or more. Dates for Tennessee Valley Authority dams are initial year of hydropower production; others are dates of closure. Sources of data: U.S. Department of the Interior (1986), U.S. Department of the Army (1986), van der Leeden et al. (1990).



	DAM	RESERVOIR	RIVER	STATE	CAPACITY	DATE
1	Hoover	Mead	Colorado	AZ/NV	28,500,000	1936
2	Glen Canyon	Powell	Colorado	AZ	27,000,000	1964
3	Garrison	Sakakawea	Missouri	ND	23,923,500	1956
4	Oahe	Oahe	Missouri	SD	23,337,600	1962
5	Fort Peck	Fort Peck	Missouri	MT	18,909,000	1940
6	Grand Coulee	F.D. Roosevelt	Columbia	WA	9,390,000	1942
7	Kentucky	Kentucky	Tennessee	KY	6,129,000	1944
8	Libby	Libby	Kootenai	MT	5,809,000	1972
9	Fort Randall	Francis Case	Missouri	SD	5,603,000	1953
10	Bull Shoals	Bull Shoals	White	AK	5,408,000	1952
11	Denison	Texoma	Red	TX	5,312,300	1944
12	H.S. Truman	H.S. Truman	Osage	MO	5,202,000	1982
13	Shasta	Shasta	Sacramento	CA	4,550,000	1945
14	Sam Rayburn	Sam Rayburn	Angelina	TX	3,997,600	1965
15	Eufaula	Eufaula	Canadian	OK	3,825,400	1964
16	Flaming Gorge	Flaming Gorge	Green	UT	3,788,700	1964
17	Hungry Horse	Hungry Horse	S.F., Flathead	MT	3,470,000	1953
18	Table Rock	Table Rock	White	MO	3,462,000	1959
19	Dworshak	Dworshak	N.F. Clearwater	ID	3,453,000	1972
20	Clarks Hill	Clarks Hill	Savannah	SC	2,900,000	1952
21	Grears Ferry	Grears Ferry	Little Red	AR	2,844,000	1962
22	Hartwell	Hartwell	Savannah	GA	2,842,700	1961
23	Blackley Mt.	Ouachita	Ouachita	AK	2,768,500	1955
24	John H. Kerr	Kerr	Roanoke	VA	2,750,300	1952
25	Red Lake	Red Lake	Red Lake	MN	2,680,000	1951
26	Wright Patman	Marion	Sulphur	TX	2,654,300	1957
27	Cooper	Cooper	Santee	SC	2,560,000	1985
28	Buford	Sidney Lanier	Chattahoochee	GA	2,554,000	1956
29	Norris	Norris	Clinch	TN	2,552,000	1936
30	John Day	Umatilla	Columbia	OR/WA	2,500,000	1968
31	Painted Rock	Painted Rock	Gila	AZ	2,491,700	1959
32	Trinity	Clair Engle	Trinity	CA	2,450,000	1962
33	New Melones	New Melones	Stanislaus	CA	2,400,000	1979
34	Tuttle Creek	Tuttle Creek	Big Blue	KS	2,346,000	1962
35	Elephant Butte	Elephant Butte	Rio Grande	NM	2,110,000	1916
36	Center Hill	Center Hill	Caney Fork	TN	2,092,000	1948
37	Barkley	Barkley	Cumberland	KY	2,082,000	1964

	DAM	RESERVOIR	RIVER	STATE	CAPACITY	DATE
38	Canyon Ferry	Canyon Ferry	Missouri	MT	2,050,519	1954
39	San Luis	San Luis	San Luis	CA	2,040,000	1967
40	Whitney	Whitney	Brazos	TX	1,999,500	1953
41	Norfolk	Norfolk	North Fork	AR	1,983,000	1943
42	Marshall Ford	Travis	Colorado River	TX	1,953,936	1942
43	Beaver	Beaver	White	AR	1,952,000	1963
44	Big Bend	Sharpe	Missouri	SD	1,884,000	1964
45	Millwood	Millwood	Little	AK	1,854,930	1966
46	Red Rock	Red Rock	Des Moines	IA	1,830,000	1969
47	Keystone	Keystone	Arkansas	OK	1,737,600	1964
48	Navajo	Navajo	San Juan	NM	1,708,600	1963
49	Dale Hollow	Dale Hollow	Obey	TN	1,706,000	1943
50	Stockton	Stockton	Sac	MO	1,674,000	1969
51	American Falls	American Falls	Snake	ID	1,670,000	1978
52	Monticello	Berryessa	Putah	CA	1,600,000	1957
53	Sardis	Sardis	L. Tallahatchie	MS	1,570,000	1940
54	McNary	McNary	Columbia	OR/WA	1,550,000	1953
55	Cherokee	Cherokee	Holston	TN	1,541,000	1942
56	Oologah	Oologah	Verdigris	OK	1,519,000	1963
57	Douglas	Douglas	French Broad	TN	1,461,000	1943
58	Fontana	Fontana	L. Tennessee	NC	1,443,000	1945
59	Clarence Cannon	Mark Twain	Salt	MO	1,428,000	1983
60	Palisades	Palisades	S.F., Snake	ID	1,401,000	1957
61	Stanford	Meredith	Canadian	TX	1,382,478	1965
62	Broken Bow	Broken Bow	Mountain Fork	OK	1,368,230	1968
63	Tiber	Elwell	Marias	MT	1,368,157	1956
64	Kaw	Kaw	Arkansas	OK	1,348,000	1976
65	Roosevelt	Roosevelt	Salt	AZ	1,336,700	1936
66	Yellowtail	Bighorn	Bighorn	WY	1,328,360	1966
67	Fort Gibson	Fort Gibson	Grand	OK	1,284,400	1953
68	North/ Dry Falls	Banks	Columbia	WA	1,280,000	1951
69	Island Park	Island Park	Henry's Fork	ID	1,280,000	1938
70	Tenkiller	Tenkiller	Illinois	OK	1,230,000	1952
71	Coolidge	San Carlos	Gila	AZ	1,222,000	1928
72	Abiquiu	Abiquiu	Rio Chama	NM	1,212,000	1963
73	Kinzua	Kinzua	Allegheny	PA	1,180,000	1965
74	Watts Bar	Watts Bar	Tennessee	TN	1,175,000	1942
75	Milford	Milford	Republican	KS	1,160,000	1965
76	Albeni Falls	Albeni Falls	Pend Oreille	ID	1,153,000	1952
77	Owyhee	Owyhee	Owyhee	OR	1,120,000	1932
78	Strawberry	Strawberry	Strawberry	UT	1,106,500	1974
79	Pickwick Landing	Pickwick Landing	Tennessee	TN	1,105,000	1938
80	Belton	Belton	Leon	TX	1,097,600	1954
81	Wheeler	Wheeler	Tennessee	AL	1,069,000	1936

	DAM	RESERVOIR	RIVER	STATE	CAPACITY	DATE
82	Guntersville	Guntersville	Tennessee	AL	1,049,000	1939
83	Alamo	Alamo	Bill Williams	AZ	1,046,310	1968
84	Seminoe	Seminoe	North Platte	WY	1,017,273	1939
85	Pathfinder	Pathfinder	North Platte	WY	1,016,507	1909
86	Folsom	Folsom	American	CA	1,010,000	1956
87	Pine Flat	Pine Flat	Kings	CA	1,000,000	1954

APPENDIX 2B

RIVERS IN THE U.S. WILD AND SCENIC RIVERS SYSTEM

The following table identifies rivers formally included in the U.S. Wild and Scenic Rivers System. Data source: American Rivers, Inc. (1990), updated to include all additions as of July 1, 1992.

	RIVER	STATE	MILES	YEAR
1	Middle Fork, Clearwater	ID	185	1968
2	Eleven Point	MO	44.4	1968
3	Feather	CA	77.6	1968
4	Rio Grande	NM	52.75	1968
5	Rio Grande	TX	191.2	1978
6	Rogue	OR	84.5	1968
7	St. Croix	MN, WI	200	1968
8	Lower St. Croix	MN, WI	27	1972
9	2nd Lower St. Croix	MN, WI	25	1976
10	Middle Fork, Salmon	ID	104	1968
11	Salmon	ID	125	1980
12	Wolf	WI	25	1968
13	Allagash	ME	95	1970
14	Little Miami	OH	66	1973
15	2nd Little Miami	OH	28	1980
16	Chattooga	NC, SC, GA	56.9	1974
17	Little Beaver	OH	33	1975
18	Snake	ID, OR	66.9	1975
19	Rapid	ID	26.8	1975
20	New	NC	26.5	1976
21	Missouri	MT	149	1976
22	Missouri	NE, SD	59	1978
23	Flathead	MT	219	1976
24	Obed	TN	45.2	1976
25	Pere Marquette	MI	66.4	1978
26	Skagit	WA	157.5	1978
27	Upper Delaware	NY, PA	75.4	1978
28	Middle Delaware	NY, PA, NJ	35	1978
29	North Fork, American	CA	38.3	1978

	RIVER	STATE	MILES	YEAR
30	Lower American	CA	23	1981
31	Saint Joe	ID	66.3	1978
32	Alagnak	AK	67	1980
33	Alatna	AK	83	1980
34	Aniakchak	AK	63	1980
35	Charley	AK	208	1980
36	Chilikadrotna	AK	11	1980
37	John	AK	52	1980
38	Kobuk	AK	110	1980
39	Mulchatna	AK	24	1980
40	North Fork, Koyukuk	AK	102	1980
41	Noatak	AK	330	1980
42	Salmon	AK	70	1980
43	Tinayguk	AK	44	1980
44	Tlikakila	AK	51	1980
45	Andreafsky	AK	262	1980
46	Ivishak	AK	80	1980
47	Nowitna	AK	225	1980
48	Selawik	AK	160	1980
49	Sheenjek	AK	160	1980
50	Wind	AK	140	1980
51	Beaver Creek	AK	111	1980
52	Birch Creek	AK	126	1980
53	Delta	AK	62	1980
54	Fortymile	AK	392	1980
55	Gulkana	AK	181	1980
56	Unalakleet	AK	80	1980
57	Klamath	CA	286	1981
58	Trinity	CA	203	1981
59	Eel	CA	394	1981
60	Smith	CA	325.4	1981
61	Verde	AZ	40.5	1984
62	Tuolumne	CA	83	1984
63	Au Sable	MI	23	1984
64	Owyhee	OR	112	1984
65	Illinois	OR	50.4	1984
66	Loxahatchee	FL	7.5	1985
67	Horsepasture	NC	4.2	1986

	RIVER	STATE	MILES	YEAR
68	Cache la Poudre	CO	76	1986
69	Black Creek	MS	21	1986
70	Saline Bayou	LA	19	1986
71	Klickitat	WA	10	1986
72	White Salmon	WA	9	1986
73	Merced	CA	113.5	1987
74	Kings	CA	81	1987
75	Kern	CA	151	1987
76	Wildcat Creek	NH	14.5	1988
77	Sipsey Fork, West Fork	AL	61.4	1988
78	Big Marsh Creek	OR	15	1988
79	Chetco	OR	44.5	1988
80	Clakamas	OR	47	1988
81	Crescent Creek	OR	10	1988
82	Crooked	OR	15	1988
83	Deschutes	OR	173.4	1988
84	Donner und Blitzen	OR	72.7	1988
85	Eagle Creek	OR	27	1988
86	Elk	OR	19	1988
87	Grande Ronde	OR	43.8	1988
88	Imnaha	OR	77	1988
89	John Day	OR	147.5	1988
90	Joseph Creek	OR	8.6	1988
91	Little Deschutes	OR	12	1988
92	Lostine	OR	16	1988
93	Halheur	OR	13.7	1988
94	McKenzie	OR	12.7	1988
95	Metollus	OR	28.6	1988
96	Minam	OR	39	1988
97	North Fork, Crooked	OR	32.3	1988
98	North Fork, John Day	OR	53.8	1988
99	North Fork, Malheur	OR	25.5	1988
100	N. Fk., M. Fk., Willamette	OR	42.3	1988
101	North Fork, Owyhee	OR	9.6	1988
102	North Fork, Smith	OR	13	1988
103	North Fork, Sprague	OR	15	1988
104	North Powder	OR	6	1988
105	North Umpqua	OR	33.8	1988

	RIVER	STATE	MILES	YEAR
106	Powder	OR	11.7	1988
107	Quartzville Creek	OR	12	1988
108	Roaring	OR	13.7	1988
109	Salmon	OR	33.5	1988
110	Sandy	OR	24.9	1988
111	South Fork, John Day	OR	47	1988
112	Squaw Creek	OR	15.4	1988
113	Sycan	OR	59	1988
114	Upper Rogue	OR	40.3	1988
115	Wenaha	OR	21.6	1988
116	West Little Owyhee	OR	57.6	1988
117	White	OR	46.5	1988
118	Bluestone	WV	17	1988
119	Rio Chama	NM	24.6	1988
120	Middle Fork, Vermillion	IL	17.1	1989
121	East Fork, Jemez	NM	11	1990
122	Pecos	NM	20.7	1990
123	Clarks Fk., Yellowstone	WY	20.5	1990
124	Niobrara	NE	95	1991
125	Missouri	NE	39	1991

3

Hydrologic Science: Keeping Pace with Changing Values and Perceptions

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ABSTRACT

Hydrology as a science has evolved from roots in very pragmatic concerns about water supply, irrigation, and hydropower toward a place as a distinct geoscience in its own right. This evolution has occurred by virtue of an expanding base of knowledge on complex interactions in large-scale natural systems involving water and also because of changing values and perceptions involving protection of the natural environment. In this paper some of the major ideas behind the evolution of research and education in hydrological science are sketched. Recent trends in hydrological science and in societal values/perceptions are used to illustrate how we might profitably attempt to shape education and research in the future.

INTRODUCTION

Science is organized knowledge.

Herbert Spencer

The knowledge base of hydrological science, as with any science, grows and changes as the science matures. The facts, the theories, and the unresolved questions that are part of water science arguably have accumulated at an accelerating rate over the past several decades. This changing knowledge base should influence educational programs and should inform decisions about future research programs. The progress of hydrology occurs within a broad cultural context, however, and is consequently influenced by changes in the values and perceptions of society, as well as by the perceptions of scientists. Stressing issues related to water quality, I will present some ideas on recent trends in hydrological science and in societal values/perceptions to illustrate how we might profitably attempt to shape education and research in the future.

THE EVOLUTION OF HYDROLOGY

There are no such things as applied sciences, only applications of science.

Louis Pasteur

I shall not try to recount, even briefly, the history of hydrology here. (Accounts of varying length can be found in Biswas, 1972; Nace, 1974; and NRC, 1991.) Suffice it to say that, because of the very pragmatic concerns of water supply, transportation, irrigation, and the like, the roots of hydrology stretch back to the earliest civilizations. In fact, it can be argued that, until quite recently, pragmatic considerations dominated the approach to hydrology (see, e.g., Dooge, 1988).

Although the existence of specialized textbooks implies that hydrology was recognized as a subject of modern scientific study by at least the dawn of the twentieth century, hydrology was not formally recognized as a distinct branch of geophysics until 1922, when the International Association of Hydrological Sciences (IAHS) was formed as a branch of the International Union of Geodesy and Geophysics. In 1930 the American Geophysical Union created its Section of Hydrology.

Despite formal acceptance as a branch of the geophysical sciences by national and international organizations, hydrology has failed to establish a separate identity as a geoscience. This must change if the science is to continue to advance apace (NRC, 1991; Eagleson, 1991).

> How have our perceptions of hydrology changed? Hydrologic science can now be seen as a geoscience interactive on a wide range of space and time scales with the ocean, atmosphere, and solid earth sciences as well as with plant and animal sciences. The new perceptions concern the interaction of the components and the range of scales.
>
> Our perceptions of the necessary administrative boundaries also have changed. The ubiquity of water on the earth and its indispens

> ability to life do not make hydrologic science out of all geoscience and biology. Forging a separate identity for hydrologic science requires specifying and claiming its central elements, and locating its administrative boundaries as a flexible compromise between precedent and scientific completeness. (NRC, 1991)

The above quote from the report of the Water Science and Technology Board's (WSTB) Committee on Opportunities in the Hydrologic Sciences (COHS) suggests that definition of hydrology as a distinct discipline within the geosciences is essential to the timely expansion of our knowledge base. The "boundaries" of hydrology identify it as distinct from but touching upon atmospheric and ocean sciences (Figure 3.1). The COHS went on to conclude that a fresh approach to hydrology was needed:

> Thus the science of hydrology has come to encompass a mix of natural and altered physical, chemical, and biological systems as well as to include important interactions with the engineering and social sciences. There is little doubt that coping with these issues will require

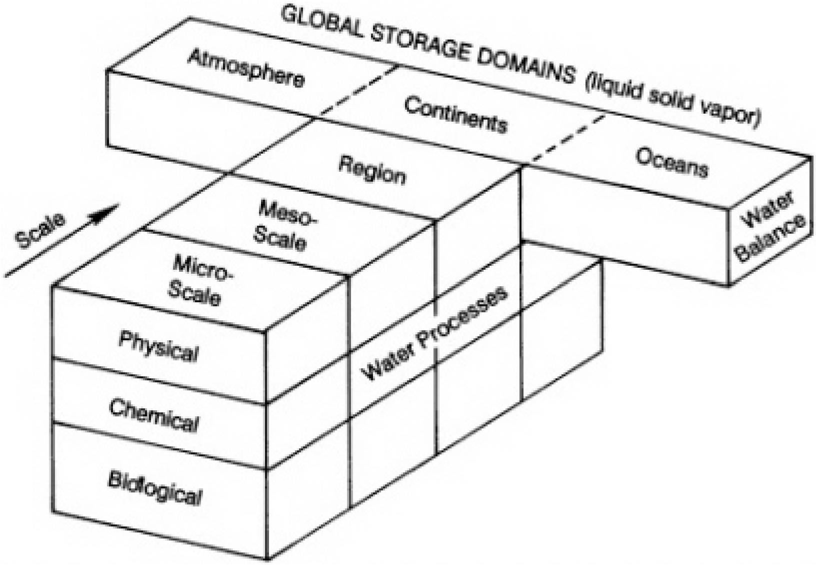

Figure 3.1 Hydrologic science: a distinct geoscience (NRC, 1991).

> a much-improved scientific understanding of the earth system and its component parts. Unified and coherent treatment of hydrologic science is central to this larger effort. (NRC, 1991)

The evolution of hydrology, and its relation to the work of the WSTB over the past 10 years, can be illustrated by considering questions involving water quality. In 1969 William Ackerman presented a paper at the First International Symposium for Hydrology Professors entitled "Scientific Hydrology in the United States." Ackerman (1969) saw a deficiency in hydrology in the area of water quality:

> With regard to environmental quality, it seems to me that classical, as well as modern hydrology, are seriously weak in the almost exclusive attention to quantitative aspects. With the exception of sedimentation we have virtually excluded water quality as a parameter of water science.

Although Ackerman's assertion might be challenged on the basis that hydrogeologists had been concerned with water quality in the broad scientific sense long before 1969, I think his view reflects the notion at the time that hydrology was primarily a field of engineering that had relegated issues of water quality to its sibling field of sanitary engineering. Certainly, there was no dearth of interest in or work on water treatment and wastewater treatment in the engineering community. Much of this work represented "scientific" accomplishments in support of the engineering objective of producing potable water. One of the early reports of the WSTB reflects this particular emphasis regarding water quality—a report on the operation, maintenance, and performance of an experimental water treatment plant on the Potomac estuary (NRC, 1984).

The view of hydrology as a distinct earth science, as espoused by the COHS and endorsed by many scientists including me, explicitly includes water quality issues (see, e.g., Figure 3.1) with critical areas reflecting the change from concerns for technological solutions to relatively small-scale problems to concerns for protection of the natural environment at regional and global as well as local scales (NRC, 1991). For example, the COHS report notes several areas of current concern: a lack of understanding of global biogeochemical cycles; of geochemical processes on hillslopes; and of the fate and transport of contaminants in hydrological systems, particularly of contaminants released into soils and ground water. This increased attention to biogeochemical processes in the natural environment does not negate the continued importance of water treatment, of course. Rather, it indicates changes in the awareness of hydrological scientists of the need to gain fundamental understanding of the functioning of natural systems and, in a more applied sense, to deal with such topics as the transport of contaminants by ground water.

This increasing emphasis on the quality of ground water is actually reflected in the reports of the WSTB over its history—from a report on protection of the quality of ground water (NRC, 1986) to the report of a colloquium on science, policy, and public perception related to remediation of contaminated soil and ground water (NRC, 1990a) to a thorough review of the use of ground water models in both scientific and regulatory applications (NRC, 1990b). In fact, even the early report on the experimental treatment plant on the Potomac estuary (NRC, 1984) recognized that limitations on a full assessment of the feasibility of the engineering schemes were, in part, due to a lack of scientific understanding of the fate and transport of contaminants <u>in the natural environment</u>: "Accurate characterization of most nonconservative quality parameters is virtually impossible considering the multiplicity of complex, natural processes and factors controlling their degradation and transformation. The precise nature and kinetics of these reactions in the estuary are currently unknown" (NRC, 1984).

Furthermore, the limitations of technological "fixes" to environmental problems came to be widely recognized (NRC, 1990a). Failure to recognize limitations can lead legislation- and regulation-driven solutions to ground water remediation to be less than cost effective (Freeze and Cherry, 1989). The linkages of the strictly physical, chemical, and biological aspects of scientific hydrology with the social science aspects of water resources planning and management become even more important under these conditions.

THE EVOLUTION OF HYDROLOGICAL RESEARCH

> *Where there is much desire to learn, there of necessity will be much arguing, much writing, many opinions; for opinion in good men is but knowledge in the making.*
>
> *John Milton*

Some of the impetus for the latest call for recognition of hydrology as a separate earth science discipline stems from the evolution of problems addressed in the science to greater and greater complexity and to ever-increasing time and space scales. Eaton (1969) pointed out that "characteristic of the current focus is that hydrology and hydrology research increasingly are involved in problems of great complexity because of both the magnitude of the undertaking—e.g., the Trans-Texas Canal—and also because of the interaction of hydrologic and nonhydrologic factors—e.g., regulation of Everglades water levels." Freeze and Back (1983), in the preface of their compendium of classic papers in physical hydrogeology, argue that there have been three "revolutions" (in the sense used by Kuhn in his 1962 book) in physical hydrogeology and that the scale and complexity of problems addressed have grown with each one. The first revolution grew from Darcy's work (published in 1856) and focused work on the column scale (application to sand filters). The second stemmed from the work of Theis (published in 1935) and led to aquifer testing. The third revolution was a result of the introduction of digital computing to the field in the early 1960s and produced an ability to consider large-scale regional systems. The COHS report carries this argument forward, noting that the global scale must now be very seriously considered as important to hydrology.

> This realization of the importance of water to the earth system at geophysical space and time scales has profound implications for the research and educational infrastructure of hydrologic science. We cannot build the necessary scientific understanding of hydrology at the global scale from the traditional research and educational programs that have been designed to serve the pragmatic needs of the engineering community. (NRC, 1991)

How does this evolution toward ever-increasing complexity and spatial/temporal scale influence research? Our inability to deal with complexity of process and heterogeneity of geological materials at a wide range of spatial scales led Beven (1987) to conclude that hydrology faced an imminent crisis and was ripe for a scientific revolution (again in the sense used by Kuhn in his 1962 book):

> Hydrology in the future will require a macroscale theory that deals explicitly with the problems posed by spatial integration of heterogeneous nonlinear interacting processes (including the effects of preferential flow pathways ...) to provide a rigorous basis for both "lumped" and "physically-based" predictions. Such a theory will be inherently stochastic and will deal with the value of observations and qualitative knowledge in reducing predictive uncertainty; the interactions between parameterizations and uncertainty; and the changes in hydrological response to be expected as spatial scale increases. Such a theoretical framework should initiate new lines of thought, and innovative methods of measurement, analysis, and hypothesis testing to be developed during a future period of "normal" science in hydrology.

Work on a research program to define a rigorous stochastic theoretical basis for hydrology has been ongoing for several years now, but, as Beven suggests, there is not yet even near-universal agreement that this is the most fruitful course of action. Furthermore, there are "costs" associated with a transition to a stochastic basis. A stochastic theory is probably most advanced in ground water hydrology where great progress has been made in the past 15 years or so on describing the flow of water and the transport of conservative solutes through heterogeneous media (see, e.g., review by Yeh, 1992). The approach has also been extended to include transport of chemically reactive species by ground water (Lynn Gelhar, Massachusetts Institute of Technology, personal communication, August 1992). But a very significant problem arises: the data requirements and the (necessarily large-scale) field experiments to explore the implications and test stochastic theories are considerable (NRC, 1990b; Gelhar et al., 1992). Therefore, the cost of the necessary field research in hydrogeology can be expected to be substantial. This same conclusion holds true for other areas of hydrology if we are to realize Beven's goal of a scientific revolution. For example, the COHS report suggests several priority categories for research, one of which can be read to require a strongly interdisciplinary effort and a commitment to improved laboratory and field experimentation.

How does hydrological science stand in regard to funding the important research activities that are necessary to push the frontiers? Evans and Harshbarger (1969) summarized data for expenditures on research in water resources in 1966 and on projected expenditures for five years in the future from 1966, that is, 1971 (Table 3.1). The COHS collected information from federal agencies on expenditures for research in hydrological science (Table 3.2). Although it may be patently unfair to compare Tables 3.1 and 3.2, these data do seem to confirm the nagging suspicion that the progress of hydrology as a science, especially vis-à-vis other sciences, may not have been what it should.

The data in Table 3.2 also suggest that there has indeed been an increasing emphasis on research involving water quality. This reflects the changes within our society toward a greater valuation of environmental quality. A good part of this is associated with concern for remediation of contaminated soils and ground waters. It is interesting to note that the level of research funding for basic hydrology (e.g., Table 3.2) is hardly noticeable in terms of federal budgets for environmental remediation. Russell et al. (1991) place the price tag for hazardous waste remediation in this country at some $\$7.5 \times 10^{11}$ and indicate that the price could be as high as $\$1.6 \times 10^{12}$!

While it may be argued that the expenditure of large sums of money on ground water remediation will unavoidably benefit research in hydrogeology through spinoff effects, there should be some concern among the community interested in promoting hydrological science because this might be yet another example of the discipline being driven by problem solving rather than puzzle solving. Davis (1992), in a paper presented at the Remson Symposium at the 1992 American Geophysical Union Fall Meeting, summarizes the concern:

TABLE 3.1 Research Expenditures for 1966 (Estimated) and for 1971 (Projected) as Summarized from a Report by the Federal Council for Science and Technology

	Water Research Categories	$ Millions	
		1966	1971
I.	Nature of water	2.8	3.9
II.	Water cycle	15.3	24.8
III.	Water supply and conservation	22.9	26.9
IV.	Water quantity management/control	4.1	8.5
V.	Water quantity management/protection	12.2	53.8
VI.	Water resources planning	3.0	13.5
VII.	Resources data	2.3	4.0
VIII.	Engineering works	4.5	10.3
IX.	Manpower, grants, and facilities	24.7	54.0
	Total	91.9	199.3

SOURCE: Evans and Harshbarger (1969)

> The uncertain balance between practical work and flights of the intellect continues, but our modern flights seem to be unreasonably tethered to practical demands, particularly to regulatory-driven requirements. Even our funding agencies have concocted a unique series of hurdles related to practical relevancy with precognition as the first incredible step. That is, research if funded only in practical results can be seen in a crystal ball.

TABLE 3.2 Federal Funding for Research in the Hydrological Sciences for Fiscal Year 1988 (from NRC, 1991)

	Water Research Categories	$ Millions
I.	Earth crust	22.7
II.	Landforms	17.5
III.	Climatic processes	6.2
IV.	Weather processes	7.7
V.	Surficial processes	7.4
VI.	Living communities	25.2
VII.	Chemical processes	38.3
VIII.	Additional topics	2.0
	Total	127.0

What about the future? One very promising step has been the creation of a program in hydrological science within the National Science Foundation (NSF). This program appears to have as a goal furthering the agenda outlined in the COHS report (NRC, 1991). Nevertheless, the program, in and of itself, cannot satisfy the total need for hydrological research. I have argued that hydrological research must progress to include more field observation and experimentation and must increasingly do so at large spatial scales. The stimulation of research in scientific hydrology with the essential costly field components will have to be done very carefully by the NSF given the modest budget available.

THE EVOLUTION OF HYDROLOGICAL EDUCATION

> *'Tis Education forms the common mind, Just as the twig is bent, the tree's inclin'd.*
>
> *Alexander Pope*

The modern evolution of hydrological education has paralleled the evolution of the science as I have outlined above. Prior to the formation of the IAHS, not only was hydrology not recognized as a separate discipline, but there were relatively few courses taught specifically on the subject. As Ackerman (1969) wrote:

> It was my good fortune to study hydrology at the University of Wisconsin about 1934 when, I suppose, a course by this name was offered at not more than three universities in the country.

Since the 1930s, the teaching of hydrology in the United States has evolved within the problem-solving context in which the discipline was viewed. A 1974 UNESCO report on the teaching of hydrology worldwide summarized the status at that time:

> The science of hydrology has developed within many different fields of study, including civil engineering, meteorology, geology, physical geography, and geophysics and it has thus been difficult for it to emerge as a separate branch. In fact hydrology has been established as a separate field of study in only a few of the largest and most highly developed countries.

The "most highly developed countries" have made precious little progress since the 1974 UNESCO report marking the end of the International Hydrological Decade, however, and it is becoming ever more clear that these countries, including the United States, need to assume the leadership role to change matters.

As I have indicated, a major push for reform of hydrology education along the lines of recognizing hydrology as a distinct earth science discipline came through the efforts of the WSTB (NRC, 1991; Eagleson, 1991). But there are other voices as well. In 1989, when Vit Klemes was president of IAHS, he established a panel to address the intellectual content and context of hydrology education and to make recommendations accordingly. The panel suggested that hydrology had not progressed adequately over the past several decades and concluded that a revamping of educational systems was in order.

> The challenges of hydrology can be met only through a conscious and concerted effort to consolidate and develop hydrology intensively as a coherent geoscience and as a technology resting on a sound scientific basis. Education is central to the required process of change and improvement. The present structure of hydrological education, generally tailored to the needs of specialized nonhydrological disciplines, is ill-fitted to cope with present and future requirements. (Nash et al., 1990)

The COHS report (NRC, 1991) offers some prescriptive advice on how educational efforts in hydrology should be structured. Although not everyone will agree with the COHS report (e.g., Back, 1991), it is, in my opinion, an excellent point for getting started.

I would like to stress two particular points related to education in hydrology: the need to balance the orientation toward computation with a coequal emphasis toward experimentation and the need to keep striving to encourage women and underrepresented minorities in the field. With regard to the first of these, as early as the 1969 seminar for hydrology professors, Hall (1969) expressed some concern about the potential imbalance in hydrology toward computer exercises:

> Some basic work on the physical science is being accomplished ..., but day-by-day the emphasis has shifted visibly from fundamental physics to fundamental mathematics.

Even in hydrogeology, where numerical simulation has (arguably) seen some of its greatest successes in all of the earth sciences, our computational abilities have outpaced our abilities to gather and interpret data in the field.

> The next major level of improvement in ground water simulation models will not arise from improved numerical procedures; rather, a greater investment must be made in obtaining more accurate descriptions of aquifer properties and their variability. . . . [O]n the whole we need more geology in hydrogeology. (Konikow, 1987)

Perhaps the warning of Truesdell (1984)—"Preponderance of computing discourages critical analysis, creative thought, and the training of thinkers"—is too extreme to apply to hydrology, but I do think we need to heed the warning of the recent IAHS panel:

> One urgent educational problem, which has reached crisis proportions in many universities, is the lack of field and laboratory experience. This is a problem at all levels and in many disciplines and has existed long enough to be self-perpetuating through the next generation of faculty. The consequences in hydrology are both profound and disturbing especially with the current emphasis on conceptual modeling. Although such models constitute useful tools in the investigation of the physical world, exclusive or undue reliance on them may tend to separate students from the realities they are supposed to study. In the absence of appropriate testing, models

> take on an aura of reality in the minds of their users and become a source of unsound science and practice. (Nash et al., 1990)

The second issue is the recruitment and retention of women and underrepresented minorities into the hydrological sciences. The COHS report notes that statistics suggest that hydrology does about as poorly as other physical sciences—about 10 percent of the profession are women, for example. I noted a somewhat disturbing correlation in data from an NRC report as summarized in Physics Today several months ago (Fehrs and Czujko, 1992). Countries in which a higher proportion of the physics faculty members are women graduate a higher proportion of women Ph.D.s. We should be aware of a "catch-22" aspect of the problem, if there is cause-and-effect relationship here, and be prepared to do what is necessary to break any vicious cycle. The COHS reports the prescriptive advice for changing the current imbalance. The WSTB should make sure that this agenda remains at the top of everyone's list!

HYDROLOGY AND WATER RESOURCES

> *What is all knowledge too but recorded experience, and a product of history; of which, therefore, reasoning and belief, no less than action and passion, are essential materials?*
>
> *Thomas Carlyle*

My comments in this paper have dealt almost exclusively with hydrology as a science. The complexities and difficulties facing us in devising research and educational policies and institutions to keep pace with the changing knowledge base in scientific hydrology are perhaps quite enough for a single presentation. Nevertheless, I would be remiss if I failed to point out that at least as much attention needs to be paid to the interface between scientific hydrology and the broader issues of water resources. The issue is how to promote close collaboration between natural scientists and social scientists over the long term so that the problems, issues, and policies in water resources can be adequately addressed (Evans and Harshbarger, 1969).

> One fact made clear during this committee's oversight of the San Joaquin Valley Drainage Program is that finding a solution to the valley's drainage problem, and any such situation anywhere in the West or in the world, is not a purely technical question. Indeed, the more difficult issues are often political, social, and economic (NRC, 1989).

There are no clear boundaries conveniently separating the "disciplines" of hydrology and water resources (Figure 3.2), so collaboration among diverse groups is the only sensible course of action. This type of collaboration occurs on an ad hoc basis within many institutions. Whether it should be formalized in educational and research programs remains a question for future study.

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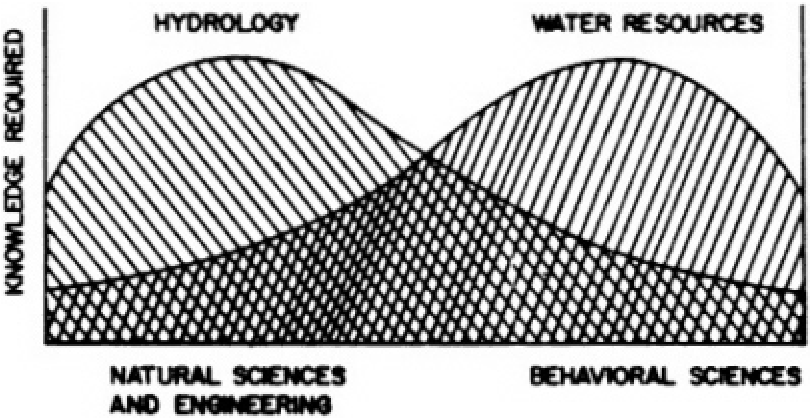

Figure 3.2 Knowledge overlap between hydrology and water resources (from Evans and Harshbarger, 1969).

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4

Changing Patterns of Water Resource Decision Making

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The emergence of the National Environmental Policy Act (NEPA) presented everyone involved in water resources with a new set of challenges that included questioning our motives and the quality of our work. Even us "good guys," whose only interest was to apply our vast technical knowledge and skills to improve the quality of life for the body politic, were suspect!

In my view the NEPA permanently changed the landscape for engineers, scientists, and everyone else involved in water resource issues—by altering the character and scope of acceptable professional practices.

The 91st Congress intended to accomplish a great deal when it passed the National Environmental Policy Act of 1969, by proclaiming a statement of national policy and prescribing a methodology to accomplish those ends (and doing all that with extraordinary brevity). Section 101 (a) of Title I declares that:

> The Congress, recognizing the profound impact of man's activity on the interrelations of all components of the natural environment, particularly the profound influences of population growth, and new and expanding technological advances and recognizing further the critical importance of restoring and maintaining environmental quality to the overall welfare and development of man, declares that it is the continuing policy of the federal government, in cooperation with state and local governments, and other concerned public and private organizations, to use all practicable means and measures, including financial and technical assistance, in a manner calculated to foster and promote the general welfare, to create and maintain conditions under which man and nature can exist in productive harmony, and fulfill the

> social, economic, and other requirements of present and future generations of Americans.

The act also declared that the Environmental Impact Statement (EIS) was a process to reveal, consider, and evaluate what was proposed. While directed exclusively at federal agencies and other actions of the federal government, it effectively compelled everyone to examine and address the environmental consequences of actions that were being considered. For the engineering communities, it imposed the obligation to consider these issues early in the predesign process so that undesirable effects could be avoided or mitigated.

However, even though many believe otherwise, NEPA did not provide an avenue for individuals or organizations to prevent actions from taking place. Neither does it give authority to stop an action even if it were undeniably environmentally destructive. Rather, it assumes that the remedy for such extreme acts is embodied in the full disclosure that an EIS requires and that the political process is sufficiently robust to control such reprehensible acts. The early prominent role of the courts in addressing EIS complaints was to consider whether an EIS was required or to determine whether an EIS that had been prepared was adequate. After more than two decades, the smoke and thunder about those issues appears to have significantly abated.

Special interests take various forms, sometimes in support of an activity, sometimes opposed. The label "special interest" has come into relatively common and popular use. While the NEPA was intended to help ensure that innovators did not do something stupid and contrary to the public welfare, unfortunately it also provided avenues for those in opposition to derail or delay actions, off times for private reasons.

Development, economic growth, population growth, energy use, transportation, conservation, and pollution all directly affect water resources. These are contentious issues because our society has not yet reached a consensus about how to address or resolve them. However, while it may have slowed the pace of certain actions, it seems clear to me that NEPA has helped society to better articulate and define these complex issues in the process.

Before long the NEPA model and concepts were emulated by many of the states, and the requirement to address such perplexing questions was no longer delimited by a project's involvement by federal agencies or federal funds—everybody was doing it! Many from the engineering community initially viewed this as an unwarranted intrusion into their professional domain. There were many cries of anguish from practitioners, and other professionals who became enmeshed in complicated assessments of the consequences of practically all engineering and technical decisions and recommendations. (Admittedly some of these were pretty trivial and seemingly irrelevant.) On the other hand, some found that opportunities to prepare or respond to an EIS spawned a new "cottage industry" that became a bread-and-butter item for many consulting firms.

Once the compelling character of this short but sweeping legislative initiative sunk in, it became clear to everyone in the water resources community that the fundamental policy issues targeted by NEPA would require new perspectives, insights, and skills. The experience over the past two decades has shown that NEPA permanently modified the culture and practices of engineers, scientists, and public officials by inculcating in them the obligation to give explicit consideration of environmental consequences of public or private acts that impinge upon the public.

While "*existing in productive harmony with nature*" fulfilling the "*social, economic, and other requirements of present and future generations* " was not part of the traditional science and engineering lexicon, neither was it a totally alien concept. However, to properly address these issues, it became apparent that individuals with relevant expertise became essential and directly involved in the process.

On March 4, 1974, with drought conditions looming large on the horizon for the Potomac basin, Congress mandated that the Secretary of the Army (acting through the Chief of Engineers):

> ... make a full and complete investigation and study of the future water resources needs of the Washington metropolitan area, including but not limited to the adequacy of present water supply, nature of present and future uses, the effect water pricing policies and use restrictions may have on future demand, the feasibility of utilizing water from the Potomac estuary, all possible water impoundment sites, natural and recharged ground water supply, wastewater reclamation, and the effect such projects will have on fish, wildlife, and present beneficial uses, and shall provide recommendations based on such investigations for supplying such needs. (NRC, 1984a)

The act also directed the U.S. Army Corps of Engineers to request the National Academy of Sciences/National Academy of Engineering to review and comment on the scientific bases for the conclusion reached in its studies of both an experimental water treatment plant for the Potomac estuary and a plan for future water supplies for the Washington metropolitan area.

In 1976 the National Research Council (NRC) agreed to undertake a study of future water supplies for the capital area, a second study of an experimental estuary water treatment plant (NRC, 1984b). Those of us involved learned a great deal. The use and abuse of the Potomac River basin had long been a matter of concern for those whose lives and livelihoods were influenced and affected by current and future uses of that water resource. The Corps of Engineers, with regulatory responsibility for the Potomac River and for the water supply of the District of Columbia (viz., the Washington Aqueduct Division) was instructed by the Congress to study and recommend a "permanent solution" to the periodic droughts that threatened the metropolitan Washington area (MWA). While applauding the idea of final resolution to these problems, many living in the area viewed the Corps' role in this endeavor with some suspicion. (It is probably fair to say that the Corps at that time was thought by many to be dam-building zealots—and these views were reinforced by somewhat strident attacks on all large dam construction [see, e.g., Peterson, 1954].)

Congress's directive to the Secretary of the Army to request a review of the scientific conclusions reached in its report was intended to allay the suspicions of skeptics. The committee, on the other hand, was eager to prod the Corps into producing an exemplary study that would be a model for future water supply studies. Dan Okun, chairman of the study (in collaboration with Sheila David and Charlie Malone) recruited a committee for this task that included scholars and practitioners from economics, public administration, ecology, hydrology, systems engineering, and water supply engineering. Under Dan's leadership the committee concluded that it would be more effective and useful if it advised the Corps on its approaches and design for the studies as they evolved in addition to reviewing the final results, conclusions, and recommendations after the studies were completed.

The skills and competence needed to address the broad range of issues confronting the Corps in a study involving a 50 year planning horizon for the nation's capital dictated that the composition of the committee include members with expertise beyond the engineering aspects of public water supply systems. The amount of water supply capacity needed for the MWA required that methods for forecasting future demands for water would have to be developed; the biological, social, and political consequences of candidate impoundment (dam) sites would have to be evaluated; and the biological and chemical impacts on the estuary of withdrawals of water from the Potomac during drought periods would have to be analyzed and assessed.

> The determination of future water resource needs and the means for satisfying these needs are only, in part, "*scientific*" questions. At the same time, proposed solutions to any engineering problem require judgment in order to balance technical and economic factors and issues of political feasibility and acceptability. The major questions the Corps of Engineers addressed required not only careful develop

> ment of the facts of the Metropolitan Washington Area (MWA), but also extrapolations of this information to a time some 50 years in the future. The time periods selected for planning such works may vary, as will the physical, chemical, biological, political, economic, social, and demographic environments of any study that strives to determine future water resources needs. (NRC, 1984a)

As the study neared completion, Professor William Corcoran (of Cal Tech), then a member of the NRC's Assembly of Engineering, recommended that the NRC recognize the need for a focused and visible effort directed at current and emerging water resource issues, especially within the federal agencies. After receiving much attention during the 1960s, the federal government dismembered many of the water resource policy-making structures it had created and left little to replace them. Thus, the NRC established the Water Science and Technology Board (WSTB), a body that could render advice to all federal agencies on matters pertaining to freshwater resources. It seems that the NRC acted wisely.

The kinds of advice that agencies sought and continue to seek from the WSTB have done much to shape the composition of the committees, panels, and the board itself. At the outset the questions posed centered primarily on engineering issues. But more and more the agencies were confronted with matters that were more comprehensive in scope and that demanded a broader range of skills and knowledge, which the board sought to provide on its panels and committees.

Accordingly, as shown in Figure 4.1, the composition of the panels and committees (and the board itself) reflected a changing array of issues ranging from engineering, the physical sciences, the social sciences, and public health.

I would be remiss if I did not call attention to an important accomplishment of the WSTB, namely, the recruitment of women engineers and physical and social scientists to serve on its committees. The staff (in the beginning by Sheila David) rendered a real service to the board through its efforts to identify women who were qualified to participate. It was soon discovered that the relatively low level of participation by women in these activities was less a matter of scarcity than identification. The payoff from the efforts of Sheila David and other members of the staff are also shown in Figure 4.1.

The extent of the importance and of the value of the board's work is reflected, in part, by the number of its sponsors as well as its productivity, as shown in Figure 4.2.

In conclusion, I believe that the National Environmental Policy Act has had a profound and lasting impact. It made all of us aware of and accountable for the planning, design, and operation of water resource systems. It has enlarged the context in which water resource issues are addressed. And most significantly it has helped us to internalize the social, public policy, and technical concerns and issues that ought to be included in assessing how water resources should be used. These changes have already influenced how we train and educate water resource professionals.

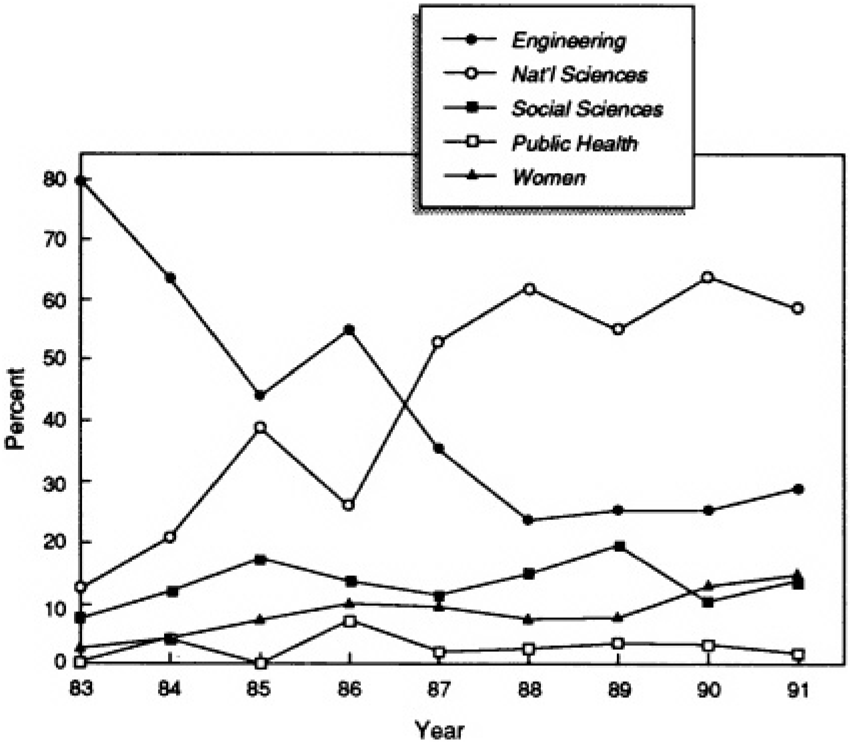

Figure 4.1 Composition of WSTB committees in engineering, natural sciences, social science, public health, and percentage of females.

The WSTB has much to celebrate on its tenth anniversary. I believe the reasons for establishing the board are as valid today as they were a decade ago. If anything, water resource issues have become more critical in the face of the demands imposed by a growing U.S. population, burgeoning environmental insults, and global threats. Given the complexity of the issues and the off times political spin imposed solutions by the federal agencies, the WSTB provides a unique forum where these matters can be addressed in ways that assure independent and autonomous assessments. Congratulations!

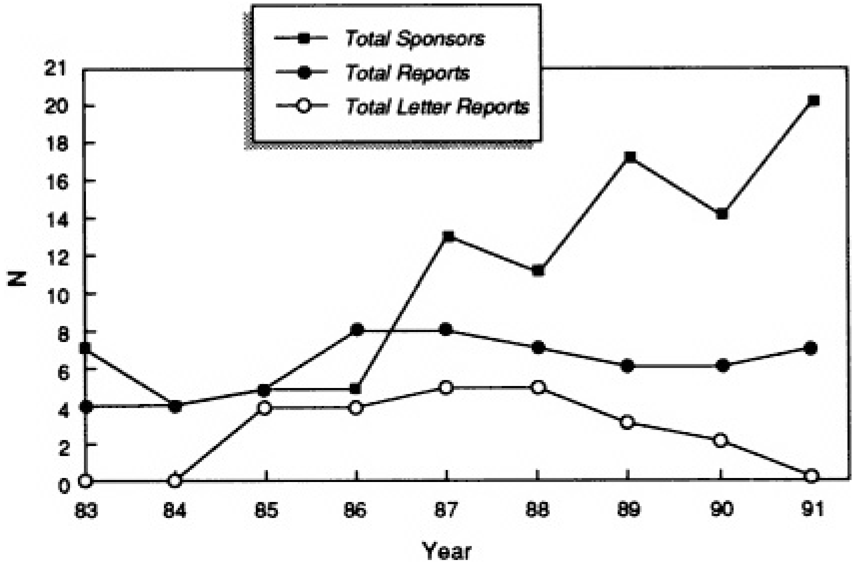

Figure 4.2 Growth of WSTB sponsors and reports from 1983 to 1991.

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5

Changing Water Resources Institutions

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> Institutions are the humanly devised constraints that structure political, economic and social interaction. They consist of both informal constraints (sanctions, taboos, customs, traditions, and codes of conduct), and formal rules (constitutions, laws, property rights). Throughout history, institutions have been devised by human beings to create order and to reduce uncertainty in exchange. Together with the standard constraints of economics they define the choice set and therefore determine transaction and production costs and hence the profitability and feasibility of engaging in economic activity. They evolve incrementally, connecting the past with the present and the future; history in consequence is largely a story of institutional evolution in which the historical performance of economics can only be understood as part of a sequential story. Institutions provide the incentive structure of an economy; as that structure evolves, it shapes the direction of economic change towards growth, stagnation, or decline. (North, 1991, p. 97)

The nation's water institutions establish the opportunities as well as the incentives to use, abuse, conserve, or protect water resources. They determine

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* This paper draws extensively on his chapter, "Water Resources: Increasing Demand and Scarce Supplies," in K. D. Frederick and R. A. Serlio, eds., America's Renewable Resources: Historical Trends and Current Challenges (Washington, D.C., Resources for the Future, 1991).

how trade-offs among alternative water uses are made and whether high quality water is available for or a constraint on the provision of safe drinking supplies, new development opportunities, water-based recreation, and/or fish and wildlife habitat. This paper sketches broad changes in the use and management of the nation's water resources and suggests how key institutions have influenced these changes and the overall benefits the nation derives from its water resources. The paper also considers the adaptability of these institutions to changes in the supply and demand for water.

The following discussion of the use and management of America's water resources over the past 200 years is divided into three broad stages. The first stage, which ended about 1900, was a period when demands on the resource were small relative to supplies, the ability to control flows was very limited, and natural supplies shaped the exploration, settlement, and development of the country. The second stage, which extended from about 1900 to 1969, was a period of rapid growth in water use and in our capacity to control supplies and of general neglect as to the impacts of human activities on stream flows and water quality. The third stage is characterized by ongoing attempts to mitigate the effects of past abuses and to deal with sharply rising water costs, increasing competition for available supplies, and changing values. The elements of a fourth stage in which future institutions provide appropriate incentives to conserve and protect the resource and opportunities to transfer resources readily in response to changing supply and demand conditions are outlined in a concluding section.

THE NINETEENTH CENTURY

The natural availability of water had a strong influence over the exploration and development of the country during the nineteenth century. Rivers were the principal routes for exploration and trading, cities grew up around major rivers and harbors, factories were located beside streams to harness the power of flowing water, and agriculture was located where precipitation was adequate or a stream could be easily diverted for irrigation. With little capacity to control natural flows, either too much or too little water was an obstacle to developing about one-third of the original 48 states. Floods inhibited development in the Mississippi, Missouri, and Sacramento river basins, and the lack and unreliability of precipitation limited settlement in much of the West.

Canals, constructed primarily by state and private interests, were the principal water projects undertaken during this century. Federal influence over water development came largely through policies designed to encourage settlement of flood-prone, semiarid, and arid areas. The Swamp Lands acts of 1849 and 1850 provided free federal lands to states along the lower Mississippi River under the condition that funds from the sale of the lands be used for flood control and drainage. The Homestead Act of 1862 helped push the frontier west by providing settlers free title to 160 acres after five years of residence and cultivation. Further encouragement for settlements in areas with little precipitation was provided by the Timber Culture Law of 1873, the Desert Land Law of 1877, and the Carey Land Act of 1894. These acts relaxed ownership requirements for settlers in arid and semiarid areas and encouraged irrigation and land reclamation.

States reserve the right to control the waters within their borders that are not encumbered by federal law or interstate compact. The earliest state water laws governing surface-water use were based on the common law doctrine of riparian rights. These rights restrict water use to lands adjacent to a stream and to "reasonable" uses that do not place undue burdens on other riparian users. All riparian owners are required to curtail use during periods of shortage. This doctrine worked well where streams were abundant and when demands on the resource were modest. But in the West where streams are less common and flows are smaller and less reliable, the constraints on movements of water to nonriparian lands and the uncertainty of supplies associated with these rights were a serious impediment to development.

Prior appropriation became the primary basis of water law in the 17 western states. Appropriative rights are established by withdrawing water from its natural source and putting it to beneficial use. During periods of shortage, water supplies are allocated according to the principle of "first in time, first in right"; junior appropriators receive no water unless supplies are sufficient to provide the owners of senior rights with their full allotment. This allocation system provides a powerful incentive for the early diversion of stream flows. And the provision that unused rights can be lost gives appropriators an incentive to "use it or lose it." Instream flows are sacrificed under the appropriation doctrine. But this was not a source of much concern for settlers worried about the unreliability of supplies from unregulated western streams.

By the end of the nineteenth century the welfare and even the survival of countless people living in arid, semiarid, and flood-prone areas depended on benign precipitation patterns. The more easily irrigated lands were already developed, and drought as well as the low summer flows traditional of many western streams were a major source of uncertainty to holders of junior water rights. Additional irrigation development depended increasingly on storage to expand dependable supplies, but many irrigators and privately financed irrigation projects were already heavily in debt. Government support was widely considered to be essential for the future growth of irrigation and the overall economic development of the West.

THE CONSTRUCTION ERA: 1900-1969

The twentieth century ended a long period during which there had been little progress in the technology for developing and using water. Mechanical power replaced wheelbarrows and mules as the principal means of moving earth early in the century. Improvements in the production and use of concrete expanded the possibilities for constructing dams. New pumping technologies made it feasible to tap ground water supplies from greater depths and to transport water greater distances. And the development of hydroelectric power and electric transmission technologies provided a powerful new stimulus for undertaking water development projects.

The most important achievements in terms of their impact on human health and welfare were in the provision of drinking water supplies, a major source of debilitating and deadly disease during the previous century. Cholera during the first half of the nineteenth century and typhoid during the latter half were the waterborne diseases of particular concern. Improved filtration techniques made major improvements in drinking water quality possible toward the end of the nineteenth century. But it was not until 1908 that chlorination emerged as an inexpensive way to ensure the bacteriological quality of water. National drinking water standards were established in 1914, and soon thereafter the safety and quality of municipal drinking water supplies were widely taken for granted.

Bolstered by these technological advances and the ascendancy (with the start of Theodore Roosevelt's presidency in 1901) of the conservationists' view that it was wasteful to leave water resources unused that were capable of producing crops, power, or other outputs, the United States began a long period of intense water development. Building dams, canals, pumps, and other infrastructure to control and divert supplies became the accepted solution to virtually any water problem during this period. Large multipurpose dams became symbols of farseeing humane management of natural resources, and water planners sought to provide municipal and industrial users with virtually unlimited supplies at the lowest possible financial cost.

The federal government became a major player in developing the nation's waters. The Reclamation Act of 1902 established the Reclamation Service (currently the Bureau of Reclamation) to assist in developing the West through irrigation. The purview of the Corps of Engineers was broadened in 1913 to include power development and use and in 1917 to plan and construct flood control works. The Federal Power Commission was established in 1920 to sell surplus power generated from federal dams, to license nonfederal power developments on navigable waters, and to survey future water power development opportunities.

The federal role in water development expanded further in the 1930s as water development projects took on a new purpose, the creation of jobs. New Deal legislation gave the president extraordinary powers to initiate and finance public works, including municipal water works, sewage plants, irrigation, flood control, and hydropower. River basin account in which power revenues are used to pay for other elements of a water project was used to justify federal support for numerous uneconomic irrigation projects. The Tennessee Valley, Authority (TVA), created in 1933 with responsibility for all water-related functions of the federal government in the Tennessee River basin, had transformed the Tennessee River from one where fluctuating flows inhibited regional development into one of the world's most highly regulated rivers within just two decades. The Soil Conservation Service (SCS), another New Deal creation, emerged as an important water developer in the 1950s when its mission was broadened to include the construction of upstream water storage facilities for flood protection and agricultural purposes. Municipal and industrial water supplies, recreation, and fish and wildlife habitat also became allowable functions of SCS reservoirs in 1956.

Four federal agencies—the U.S. Army Corps of Engineers, the Bureau of Reclamation, TVA, and SCS—were seeking to expand their roles over the use and development of water resources by the end of World War II. Moreover, the availability of generous subsidies and the "first in time, first in right" doctrine of western water law provided powerful incentives for local communities and their congressional representatives to seek federal water projects. With the federal government paying all the costs associated with flood control and navigation works and subsidizing the costs of irrigation and other project benefits, water projects were desired for the jobs and federal funds they brought to a community regardless of the net impacts of the project on the use of the resource or the nation as a whole. The demise of the National Resources Planning Board by Congress in 1943 left the executive branch without the capacity to prepare or evaluate plans for overall development of the nation's waters. The void was filled by a coalition of the congressional committees responsible for the budgets of the four construction agencies, the agencies seeking increased funding and influence, and local interests seeking federal subsidies. Political considerations dominated the allocation of federal funding for water projects. The requirement, first spelled out in the Flood Control Act of 1936, that the benefits exceed the costs was not an obstacle when a project was supported by the senators and representatives controlling the budgets of the construction agencies. When necessary, the agencies were adept at inflating the benefits and deflating the costs claimed for such projects.

The combination of these technological, economic, and political forces contributed to the rapid growth of water use and dam and reservoir construction that characterized the first seven decades of this century. Total offstream water use rose from about 40 billion gallons per day (bgd) in 1900 to 370 bgd in 1970. The number of completed clams rose from less than 3,000 at the start of the century to more than 50,000 by 1970. The cumulative storage capacity of these dams increased from 10 million to 753 million acre feet (maf). The largest increases came in the quarter century following World War II when water use increased by 200 bgd and more than 35,000 clams with a combined storage of 474 mar were completed.

Water use changes were particularly striking in the West. Although the 17 western states possess only 36 percent of the renewable supplies, they accounted for 85 percent of consumptive freshwater use in the 48 conterminous states in 1970. Irrigation, which increased from 19 million to 35 million acres during the 25 years, accounted for 92 percent of the West's consumptive use of water in 1970 and was the primary reason for the widespread depletion of western streams and ground water stocks.

Ambitious plans were developed in the 1960s to counter the growing scarcity of water in the West. The Pacific Southwest Water Plan submitted to President Johnson in 1964 proposed 17 new projects and programs, including pumping Colorado River water over the mountains into central Arizona, two big dams on the Trinity River in California and a tunnel to divert water from the Trinity to the Sacramento basin, a wider California aqueduct for delivering water to the central and southern parts of the state, and two large hydropower projects on the Colorado River at opposite ends of Grand Canyon National Park. Another proposal would transport more than 16 maf annually from the Mississippi River to the southern High Plains where irrigators were depleting the Ogallalla aquifer. The most ambitious schemes proposed to bring huge quantities of water into the western United States from Alaskan and Canadian rivers. Most of these schemes to make water plentiful where nature had not were shelved as a result of growing economic and environmental concerns.

DEALING WITH LIMITS AND CHANGING VALUES

Institutions that treat water as a free resource, planners who seek to provide irrigation regardless of economic considerations and uninterrupted supplies to municipal and industrial users under all but the most extreme droughts, and a population willing to ignore the impacts of its water uses and development projects on instream flows helped prolong the construction era. Three factors—the high cost of developing new supplies, federal budget deficits, and environmental concerns—brought the water construction era to an end about 1970. These factors are reflected in changing construction and water-use patterns. Water development projects peaked in the mid-to-late 1960s when more than 2,000 new dams and nearly 29 maf of new storage were completed annually. In contrast, from 1970 to 1982 only 1,069 new dams and less than 10 maf of storage were added annually. Per capita water withdrawals peaked in the mid-1970s, and total withdrawals peaked (at least temporarily) five years later.

The costs of developing new supplies inevitably increase over time for three reasons. First, the best reservoir sites are developed first. Second, the quantity of water that can be supplied with a high degree of probability rises at a diminishing rate as storage capacity on a stream increases. And, third, the opportunity costs of storing and diverting water increase as the number of free-flowing streams declines and the demand for instream flows rises.

The availability of federal funding for new water projects declined as the Vietnam war absorbed a larger share of the budget and as concerns over the size of the federal deficit grew. Water projects became more difficult to justify economically as the discount rates used to evaluate projects increased from 2.5 percent in the 1950s, to 3.25 percent in the early and mid-1960s, to 4.625 percent in 1969, and to as high as 8.875 percent in the 1980s. Furthermore, local enthusiasm for federal water projects waned after a 1986 law required a significant increase in local cost sharing for Corps of Engineers' projects. The Bureau of Reclamation started negotiating increased cost sharing in the late 1980s.

Evidence that the United States was paying a high price for neglecting the full environmental impacts of its water projects and uses became overwhelming during the 1960s. Numerous federal and state laws have been passed to reverse this neglect and to protect and restore the nation's waters. Indeed, since the early 1970s, environmental concerns have been the driving force behind most water-related investments, a formidable obstacle to investments in new dams and reservoirs, and an increasingly important factor in the allocation of supplies.

The National Environmental Policy Act (NEPA) of 1969 is the most important of these laws. Prior to NEPA, opponents of a water supply project had the burden of proving that the project would result in unacceptable environmental damage. Since NEPA, federal agencies have been required to assess the environmental impacts of their actions and critics have possessed a potent legal tool for opposing water projects and for proposing alternative water use. NEPA also established the Environmental Protection Agency (EPA) with responsibility for setting and enforcing water quality standards.

Environmentalists acquired several other legal hooks for preventing, stalling, or modifying water development plans. Projects that would excessively damage natural amenities are now precluded on more than 100 rivers and stretches of rivers designated under the Wild and Scenic Rivers Act of 1968. EPA is able to veto water projects on environmental grounds under section 404 of the Clean Water Act of 1972. And the Endangered Species Act of 1973, which prevents federal agencies from undertaking activities that threaten the survival or critical habitat of a species designated as endangered, has been used to delay and alter several proposed water projects. More importantly, this act is forcing major changes in the management of existing projects in the Columbia, Missouri, and Sacramento basins. Also, many states have passed laws designed to protect instream flows and limit surface and ground water development.

The Clean Water Act of 1972 established ambitious goals of restoring all navigable waters to a "fishable and swimmable" condition by July 1983 and eliminating all pollutant discharges to these waters by 1985. Conventional pollutants such as fecal coliform bacteria and organics dumped directly into the nation's surface waters through municipal and industrial pipes and ditches were considered to be the nation's principal water quality problem in 1972. Technology-based effluent standards and federal construction grants have been the principal regulatory and economic tools used to limit and treat these point-source discharges. In excess of $100 billion has been spent since 1972 to limit point-source pollutants. While the quality of many lakes, rivers, and estuaries has improved as a result, the goals of the Clean Water Act have not been met. Large additional expenditures for reducing and treating point-source discharges are anticipated. But investments to control these pollutants are encountering diminishing returns in their ability to restore streams, lakes, and estuaries.

Nonpoint sources of pollutants such as runoff from farms, urban areas, and construction sites and seepage from landfills and septic systems are now the principal sources of both conventional and toxic pollutants. Because there is no single point where these pollutants can be intercepted prior to entering a water body, the problems as well as the solutions often involve land use rather than water-use practices.

Land use is particularly important for the water quality impacts of agriculture, a major polluter of 30 percent of the nation's impaired rivers and 45 percent of the impaired lakes (EPA, 1990). Overall, agricultural policies contribute to these water quality problems by encouraging cultivation of marginal lands and use of agricultural chemicals. In 1980 the Rural Clean

Water Program was initiated to demonstrate the impact of best agricultural management practices on water quality. However, this program was never well funded or targeted to areas where it would contribute most to water quality problems. The Conservation Reserve Program established under the Food Security Act of 1985 provides farmers with an annual rent and half the cost of establishing a permanent cover on land that is offered for and accepted into the conservation reserve. Relatively few of the lands included in the reserve during the first several years under the program were in areas where they could contribute significantly to improved water quality. More recently, however, the eligibility requirements have been relaxed to include lands where erosion may not be a problem but cultivation would pose serious water quality problems.

Toxic substances present a particularly difficult regulatory challenge for several reasons. First, our knowledge as to what substances are toxic and in what doses, durations, and combinations is very limited, and epidemiological and laboratory studies on animals are unable to do much more than identify problems. Second, toxins are difficult and expensive to detect in the low concentrations that may be harmful. And, third, toxins are not readily eliminated from the environment. Conventional municipal treatment technologies do not remove many potential toxins. Pretreatment of industrial effluent can keep some toxins out of municipal sewage, but they may still end up in water supplies when they are disposed of in landfills or the atmosphere. In the early 1970s, burial was considered the best way to dispose of toxic substances. Currently, billions of dollars is being spent to clean up landfills that are leaking toxins into water supplies.

The Safe Drinking Water Act of 1974, which required the EPA and the states to limit contaminants in drinking water, was the first of several federal laws focusing on curbing toxic substances in water. Other major legislation motivated in part by similar concerns includes the Federal Insecticide, Fungicide, and Rodenticide Act Amendments of 1975; the Toxic Substances Control Act of 1976; the Resource Conservation and Recovery Act of 1977; the Clean Water Act Amendments of 1977; the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (Superfund); and the Safe Drinking Water Act Amendments of 1986. In addition to being a manifestation of society's concerns about human exposure to toxins, these acts reflect a growing understanding of the complexity of the problem, uncertainty as to what to do about it, and a neglect of economic considerations in dealing with it. Hundreds of billions of dollars has already been spent and tens of billions more is being spent annually to protect and improve the quality of the nation's water supplies without any attempt to determine if the benefits exceed the costs. Furthermore, there has been little effort to explore or introduce more cost effective approaches to achieving environmental goals.

INSTITUTIONS FOR BALANCING FUTURE WATER DEMANDS WITH SUPPLIES

The United States has developed an enormous infrastructure to control, transport, and put its water resources to a multitude of uses. Large water projects, however, are no longer widely accepted as symbols of farseeing and humane management of the nation's water resources. To the contrary, they often appear to be financially and environmentally costly attempts to protect special interest groups from having to adapt to increasing water scarcity. The principal task for the future is not to construct more infrastructure but to build institutions that will ensure the existing supply system and the nation's scarce water resources are managed and allocated wisely.

Improved management of existing supplies might provide relatively low-cost, environmentally benign opportunities for increasing safe water yields in some areas (Sheer, 1986). These opportunities, however, are often constrained by institutional barriers such as multistate water laws, legal constraints on collaboration among separately owned suppliers, inadequate regulations providing for conjunctive management of ground and surface supplies, and the lack of a national water policy to reconcile the differences among the multitude of federal agencies pursuing narrow and often conflicting objectives in a river basin.

While the options for further increases in reliable supplies are now limited and costly, water demands are growing with population and income growth and the increasing values being placed on instream uses. With demand growing faster than supply, water costs will continue to increase even if supplies are managed efficiently. Demand management—which includes transferring water among alternative uses in response to changing supply and demand conditions, introducing appropriate incentives to conserve, and protecting instream flows and water quality—provides the principal means of controlling the magnitude and nature of the nation's future water costs. When water is underpriced and locked into traditional uses, more of the costs take the form of constraints on development and high costs for new water users. When water bodies are not used freely for disposal of wastes, more of the costs show up as deteriorating aquatic ecosystems and health problems. On the other hand, when the full social costs are borne by the users and water can be voluntarily transferred (subject to consideration of third-party impacts), the resource is used more efficiently and the highest-value users are assured of adequate supplies.

The institutional obstacles to more effective demand management are many. Institutions rooted in an era when water was not considered to be scarce and transfers were viewed as unnecessary or unimportant limit the ability to respond to changing supply and demand conditions. Federal policies that provide irrigators with highly subsidized water and no incentives to conserve or transfer supplies to other uses encourage waste and increase overall water scarcity. Water pricing continues to treat water as a free resource, and average-cost pricing in an increasing-cost industry keeps prices below the marginal costs that would encourage more conservation and make development of some higher-cost supplies unnecessary. Neglect of economic considerations limits the benefits society derives from the enormous funds spent to protect and improve water quality. And restrictions on and uncertainties over water rights discourage water-related investments and inhibit transfers. Political factors stymie the introduction of many reforms. Two major challenges are to develop institutions for introducing environmental values into water-use and investment decisions in a balanced and expeditious way and for incorporating third-party interests into water transfer decisions without imposing high transaction costs.

During its 10 years of existence, the Water Science and Technology Board has been on the forefront in increasing our understanding of complex water resource systems, the impacts of humans on these systems, and the role of institutions in determining how water resources are used and abused. Board studies have addressed many of the issues I have discussed. Studies concerning restoration of aquatic ecosystems, appropriative and riparian water rights, use of hydropower and its environmental and social costs, water transfers in the West, irrigation-induced water quality problems, cooperation in urban water management, ground water quality protection, the cleanup of hazardous wastes in relation to water quality, and toxic substances in the Great Lakes are just a few of these. Moreover, the numerous ongoing and proposed studies suggest that the board will continue to be a major contributor to the scientific knowledge and public understanding that are essential to developing institutions that will promote wise management and use of our scarce water resources.

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6

Changing Concepts of System Management

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ABSTRACT

Ecological concepts underlying management of water resources have shifted from a deterministic world view based on balance of nature to a recognition that natural systems are inherently variable, patchy, and often require disturbance to persist. Recognition of the interdependency of ecosystem components and the importance of indirect effects also has management implications. Applying these ecological concepts dictates (1) management in the context of the ecosystem rather than managing parts as though they were in isolation and (2) use of an adaptive management scheme that is responsive to changing environmental conditions. Over the past decade committees of the Water Science and Technology Board (WSTB) have reached similar conclusions concerning water resource management. A management challenge to future research in ecology is to provide the conceptual basis for sustaining and restoring the ecological integrity of the earth's aquatic resources.

Approaches to management of water resource systems change because of shifts in societal attitudes and institutions, as described in other papers in this volume. Management approaches also change as a consequence of advances in our scientific understanding, and it is this aspect of changes in system management that is the focus of my paper. Water resource management is grounded in numerous scientific disciplines; I focus on changes in only one of those disciplines, ecology. Inclusion of a paper dealing with ecological issues in this program is in itself an indication of the developments that have taken place in water resource management over the past couple of decades. Technology-based science has always been a strong part of the education of water resource managers. A recognition of the need for ecological expertise has come about as managers have confronted the environmental consequences of water management decisions and as the nature of water resource problems has changed, for example, from point-source discharges to nonpoint source pollution.

In this paper I focus on two ecological concepts, discuss some recent developments in ecological thought relating to those concepts, consider the management implications of these developments, and end with a discussion of future challenges for ecology.

CHANGING ECOLOGICAL CONCEPTS: NATURE IN BALANCE

The first concept is one that is as much philosophical as ecological—"the balance of nature." Over the past 50 years, ecologists have gradually come to recognize that nature is not always in balance. Tansley (1935) defined the ecosystem concept and wrote: "In an ecosystem the organisms and the inorganic factors alike are components which are in relatively stable dynamic equilibrium. Succession and development are instances of the universal processes tending toward the creation of each equilibrated system." Lindeman (1942) introduced the concept of trophic levels to ecology in his study of a Minnesota lake. He wrote: "From the trophic-dynamic viewpoint, succession is the process of development in an ecosystem ... towards a relatively stable condition of equilibrium." These early thinkers in the field of ecology conceived of an ideal system that was at equilibrium, and although natural systems were perhaps imperfect versions of that ideal, their goal as ecologists was to find the mechanisms that worked to keep the system stable. This view has changed as knowledge accumulated from fields such as paleoecology. Studies demonstrated that climate varies over all time scales and that vegetation is continuously responding to these shifts. The view has changed to one that recognizes that natural systems are in a state of flux. An ecosystem is viewed as a dynamic mosaic of patches changing in different temporal patterns.

In his book *Discordant Harmonies*, Botkin (1990) traces the changes in human perception of nature that underlie our approach to science. He notes that we have moved from perceiving nature as ordered, regular, and stable to a perception of change as a natural and necessary part of the biosphere. He follows the development of scientific thought from a view of a divinely ordered, perfect, and unchanging nature to that of the earth as a complicated machine operating at steady state to today's more "organic" image with a focus on processes, a recognition that change is inevitable and that "nature is characterized by chance and randomness" (Botkin, 1990, p. 129). This nonequilibrium paradigm is widely accepted today.

One characteristic of a nonequilibrium paradigm is a recognition of the importance of disturbance in the ecosystem. Stream ecosystems are particularly dependent on natural disturbances such as flooding (e.g., Resh et el., 1988). The biological community is dependent on natural disturbance to shape the channel and create habitat, to provide inputs of resources, and to alter the numbers of predators and competitors. Without natural disturbance, for example, when stream flow is regulated, all aspects of the stream ecosystem change. The removal of floods from an ecosystem is a greater ecological disturbance than the floods.

Other characteristics of a nonequilibrium paradigm include a recognition of priority effects, such as which species happens to arrive first at a site, and a recognition of the importance of time lags. Ecosystem function measured today may be influenced by a policy or fashion in effect a hundred years ago. Consider, for example, beavers.

Long before humans began building dams, beavers were major agents for channel modification throughout much of North America. The activities of beavers greatly alter stream ecosystem function, increasing retentiveness, increasing anaerobic processes, and lengthening the turnover time of material in the streams (Naiman et el., 1988). Before the arrival of Europeans in North America, the beaver population was estimated to be 60 million to 400 million individuals, with a geographic range from the arctic to northern Mexico. Extensive removal began in the early seventeenth century largely to serve the whims of fashion. By 1900 beavers were almost extinct, and today their population is somewhere between 1 and 20 percent of their original population. Important attributes of stream ecosystem function were changed by beaver removal long before stream ecologists began any studies, and hence our understanding of stream ecosystems is derived from sites that lack the influence of an ecologically important species. As beaver populations recover, stream ecosystem function will be continuously changing as beavers alter channel morphology and hence organic matter storage. This is a very slow process, and this legacy of beaver removal will continue to alter the pattern of change in both terrestrial and aquatic systems.

A final aspect of the nonequilibrium paradigm that I will discuss is that ecosystems are viewed as dynamic patches that are changing in character of function on different time scales. This leads researchers to study not only processes within patches but also the connectivity between patches and the often accelerated activity at the interface between patches. Taking this approach in a blackwater riverine system, my colleagues and I have studied food webs and organic matter dynamics in the water column, sandy main channel sites, muddy backwater areas, woody debris that provides a stable attachment site for organisms, the hyporheic zone (deep within the streambed), and the floodplain (Meyer, 1990). Each of these "patches" has characteristic biotic communities with associated rates of organic matter processing, and each operates on a somewhat different time scale. For example, insects of the shifting sandy sediments have very short generation times, whereas many species on the more stable woody debris have only one generation per year. Each of these "patches" is also linked and interdependent; for example, the filter-feeding insects of the woody debris are dependent on organic matter in the water column for food, and sandy sediments are linked with the highly productive floodplains that provide the detritus that fuels their food web. This view of a river as a network of interconnected habitats is at the base of the river continuum concept (Vannote et al., 1980, Minshall et al., 1985), which has stimulated much recent research in lotic ecology. Our management challenge is to create a bureaucracy that is as interdependent as the natural system it manages.

CHANGING ECOLOGICAL CONCEPTS: INDIRECT EFFECTS

A second development in ecology with management implications is a recognition of the interdependency of system components and the importance of indirect effects. Ecologists have long recognized the importance of direct effects such as the response of lakes to nutrient additions from municipal wastewater. More recently, we have come to recognize that it is not just these direct and "bottom-up" effects that influence aquatic ecosystems. "Top down" and indirect effects are often equally important; as higher trophic levels are altered, there are clearly discernible effects at lower tropic levels and in other aspects of the ecosystem. This phenomenon is called a "trophic cascade" (e.g. Carpenter and Kitchell, 1988).

A study showing how the nature of the fish population in a lake can alter its thermal structure and heat content provides an example of indirect effects in nature (Mazumder et al., 1990). In either enclosures or small lakes (< 10 ha), the presence of planktivorous fish alters the thermal structure of the water column (Figure 6.1). How can this be? Where planktivorous fish are present, herbivorous zooplankton are less abundant, and algal biomass is higher and dominated by small individuals. Smaller algae have greater light absorption and scattering per unit mass, and hence high biomass of small algae is associated with lower water clarity, shallower mixing depth, and lower heat content (Figure 6.1). Where planktivorous fish are rare, herbivorous zooplankton are abundant, algal biomass is lower with proportionally fewer small individuals, water clarity is greater, heat content is higher, and mixing depth is greater. Here is a case where the presence of a higher trophic level (a fish that eats zooplankton) has a direct effect on its prey, and a series of indirect effects on lower trophic levels and on the thermal structure of the

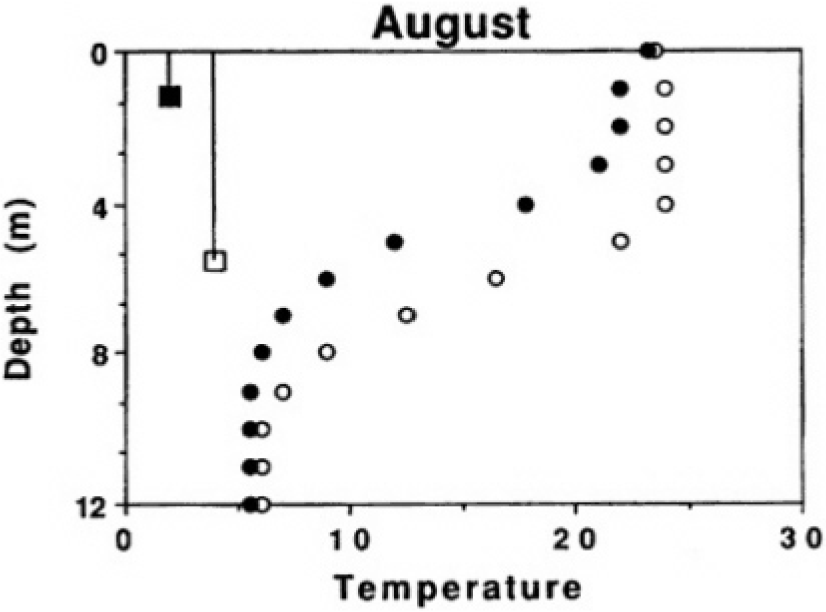

Figure 6.1 Mean Secchi depth (vertical lines on left of panel) and temperature profiles during August for lakes with low (Haynes Lake, open symbol) and high (Lake St. George, solid symbols) abundance of planktivorous fish. Both lakes had nearly identical temperature profiles in May. Heat content of Haynes Lake during August was 12.3 kilocalories/cm^2 and that of Lake St. George was 8.6 kilocalories/cm^2. Redrawn from Mazumder et al. (1990).

lake. Instead of temperature affecting biology, biology is affecting temperature! Ecologists are coming to realize that indirect effects such as this are the rule rather than the exception in ecosystems.

Although the importance of indirect effects is clear, one should not use that to justify the simplistic statement that everything is intimately related to everything else. Some relationships are stronger than others, and it is the role of the ecologist to identify the strong relationships (i.e., to determine the critical features of ecosystem structure) so that the system can be managed more wisely.

What are the management implications of these two shifts in ecological thinking? Put very simply, it means we must manage for change and for complexity (Botkin, 1990).

MANAGING FOR CHANGE

In ecological research, adoption of a nonequilibrium paradigm has resulted in a shift from a search for an endpoint to a focus on process and trajectory, with a recognition of the openness of ecosystems and the importance of disturbance. Adoption of a nonequilibrium paradigm in management will result in a similar shift as we begin to manage for change, applying management strategies designed to achieve acceptable limits of change.

One example of management for change comes from forestry. For decades forest management agencies prevented fire, seeing it as a disturbance that disrupted the stable climax forest they were trying to preserve. It soon became apparent that this was not an appropriate strategy. In sequoia forests, for example, there were few sequoia seedlings, and the understory was becoming dominated by white fir (Botkin, 1990). Rather than threatening the future of the sequoia forest, fire was necessary for successful sequoia germination and growth. Rather than being evil, fire is a necessary disturbance and an important management tool in many ecosystems.

Many aquatic ecosystems are also dependent on disturbance. A change in the natural disturbance regime is a major cause of alterations in riverine ecosystems after dam construction. For example, when disturbances caused by variable water discharge, high summer temperatures, and massive sediment transport are removed, the system changes. This has happened below Glen Canyon Dam, and it is one of the issues addressed by the WSTB's Glen Canyon Environmental Studies (GCES) (NRC, 1987) committee. Since dam construction, flood flows and sediment transport have been reduced, resulting in depletion of sand stored in the active channel (Andrews, 1991). Because of stabilized flows, a larger riparian area remains moist, and the riparian zone has expanded and been invaded by several exotic species, including salt cedar or tamarisk (*Tamarisk chinensis*), camelthorn (*Alhagi camelorum*), and Russian olive (*Elaeagnus angustifolia*) (Johnson, 1991). Release of cool, sediment-poor but nutrient-rich water from Lake Powell leads to high biomass of algae (*Cladophora*) and invertebrates in the river (Stanford and Ward, 1991). The continued existence of the native fishes is threatened by the altered thermal environment but more critically by the introduction of nonnative species that are able to thrive in the new environment created by the dam (Minckley, 1991). Native fishes are also failing to reproduce because of the absence of large seasonal changes in water level, which synchronized their breeding cycles (Minckley and Deacon, 1991). Clearly, reservoir operations that have altered the natural disturbance regime have had an effect on many components of the downstream ecosystem.

How might one manage for change in this situation? The NRC committee has advocated adaptive management (NRC, 1991a). This includes incorporating environmental dimensions into decisions on dam operation, operating the dam in an experimental mode in which different release schedules are followed to assess their effect on downstream ecosystems as well as on power generation, and ongoing scientific assessment of the downstream ecosystem to provide continued guidance to dam operators. The combination of introducing environmental dimensions at the beginning of the process, using experiments to assess ecological consequences of management activities, and continued dialogue between scientists and managers to evaluate policies in the face of a variable environment are at the core of adaptive management (Holling, 1976). The idea of adaptive management grew from a recognition of basic properties of ecological systems, which include "the unexpected can be expected" and "environmental quality is not achieved by eliminating change" (Holling, 1976). Clearly, this is managing for change.

An additional component of management for change is managing in a probabilistic and risk assessment framework in which one recognizes the inherent unpredictability of nature: in a variable world there is a finite risk of extinction (Botkin, 1990). This is particularly appropriate for managing populations of rare species (e.g., desert pupfishes) but also applies to managing a fisheries resource. Rather than determining a fixed sustainable yield, the manager recognizes that the yield should vary over time as environmental conditions vary. In the long term this produces a more sustainable yield. This type of management requires greater input of scientific understanding and continued monitoring than is currently practiced.

MANAGING FOR COMPLEXITY

How do we manage for complexity? The obvious answer, given by numerous WSTB committees (e.g., NRC, 1991a), is to manage in an ecosystem context. Rather than managing for a single resource (board feet of lumber or acre feet of water), we should manage to sustain the diversity of services provided by the ecosystem with a recognition of the complex interactions and numerous indirect effects that characterize ecological systems.

An example of an attempt at this type of management is offered by the U.S. Forest Service's (USFS) New Perspectives program, now called the Ecosystem Management program (Kessler et al., 1992). This program "involves a shift in management focus from sustaining yields of competing resource outputs to sustaining ecosystems" (Kessler et al., 1992). Earlier practices of multiple use implied that different pieces of the landscape could be set aside for different uses, which ignores the fact that the landscape is interconnected and cannot be managed as individual pieces. One of the documents stimulating this change is Forestry Research: A Mandate for Change (NRC, 1990). It proposes a research and management paradigm using an ecosystem approach that views the landscape as a living system with "importance beyond traditional commodity and amenity uses" (Kessler et al., 1992). Ecosystem management recognizes that: "If it is the entire system and its continued productivity for a wide array of uses and values that we desire, then production goals for individual resources ... might not point a path toward sustainability. We need instead objectives that relate to ecological and aesthetic conditions of the land ... and that sustain land uses and resources yields compatible with those conditions" (Kessler et al., 1992). As expressed by Salwasser (1990 in Swanson and Franklin, 1992), forestry practice has evolved from regulating uses (i.e., avoiding undesirable activities), to sustained yield management that focuses on a few desired products, to sustainable ecosystem management, which considers the well-being of the ecosystem that provides numerous goods and services.

I have been involved in the planning for an ecosystem management project in a national forest in North Carolina. I offer the following partial list of desired future conditions that are guiding watershed management as an example of how this new perspective could alter management of lands that in decades past have been managed primarily to meet a specified timber yield:

- populations of native fish species that equal or exceed current levels,
- maintenance of a diversity of stream productivity levels to maintain diverse gene pools of aquatic species, and

- stream sedimentation rates that maintain and/or enhance baseline fish reproduction and growth rates.

Ecosystem management is a very young program, and we do not know how well it will be implemented by land managers. It is a program with considerable promise. Clearly, the tasks of future WSTB committees would be very different if other federal agencies truly adopted a "new perspective" for land and water management.

The need for a new perspective in a larger landscape context on federal lands becomes particularly apparent when one considers declining biodiversity. Federal lands offer a rare opportunity to include maintenance of biodiversity as a management objective; 26 threatened or endangered invertebrate species live on USFS lands, and 69 percent of the fish species listed as threatened or endangered occur on USFS or Bureau of Land Management lands, which include 453,000 kilometers of permanent streams and 2.6 million hectares of lakes and reservoirs (Williams and Rinne, 1992). Ecosystem management in a landscape context will be necessary to maintain this national trust of biodiversity.

Another example of ecosystem management comes from the Pacific Northwest and involves management of the riparian zone. In past decades, riparian management objectives in the West have focused on controlling stream temperatures and limiting sediment input to meet water quality goals while still harvesting timber. Ecological research has shown that the riparian zone provides habitat and food resources for fish and other wildlife, provides channel structures (most important, woody debris) that modify the retentiveness of stream channels, and modifies light and nutrient availability in streams (e.g., Gregory et al., 1991). The interaction between forest and stream varies depending on the geomorphic setting of the channel; for example, wide unconstrained valleys offer more habitat and food resources for fish than do constrained valleys, but their channels also show greater lateral movement (Swanson and Franklin, 1992). This ecological understanding has been used to develop a riparian management plan based on an ecological definition of the riparian zone that permits management to achieve specific objectives (Gregory and Ashkenas, 1990). For example, to ensure sustainable salmonid populations, wider forested zones are recommended in unconstrained reaches in wide valley floors where lateral movement of the channel is more likely. The goals of basin planning are "to minimize the potential for cumulative effects, maintain potential inputs of woody debris, maintain continuous riparian corridors with structurally complex plant communities throughout the basin, and rehabilitate degraded riparian resources within the basin" (Gregory and Ashkenas, 1990). This is ecosystem management in a landscape context.

It exemplifies the type of management needed in a greater array of ecosystem types.

The need for ecosystem management that recognizes the complexity and patchy nature of the landscape is particularly apparent in the current controversy over wetlands (e.g., Alper, 1992). A functioning wetland consists of interconnected habitats with different inundation frequencies; some patches may not be wet every year. It is a patchy and dynamic landscape that will require a level of complexity in regulation that has not been characteristic of U.S. wetlands policy to date. This is a problem that the WSTB will be tackling in its second decade.

FUTURE DIRECTIONS

The current challenge for ecology is "to integrate and synthesize the ecological information available from all levels of inquiry into an understanding that is meaningful and useful to managers and decision makers" (Likens, 1992). The extent to which we take an interdisciplinary approach to ecology will dictate the extent to which we will be able to meet that challenge. Ecology is sometimes viewed as a biological science that studies the distribution and abundance of organisms. This is an outmoded view of ecology and one that does not serve the needs of our time.

Ecology is an integrative science that investigates the linkages among and between biotic and abiotic components of the environment. The Sustainable Biosphere Initiative, a recent visionary document produced by the Ecological Society of America (Lubchenco et al., 1991) is based on this view of ecology as an integrative science and recognizes the need for an integrated multidisciplinary approach to solving environmental problems. This offers a challenge to educators as well as researchers and managers. The recent WSTB volume Opportunities in Hydrologic Sciences (NRC, 1991b) provides suggestions on ways to achieve an integrated approach. Studies currently being contemplated by the WSTB on the science of inland aquatic ecosystems could provide further guidance in this area.

Current problems in water resource management offer numerous challenges to the ecologist. With the concern over salmon stocks and similar issues in the news, water managers recognize that water is not simply a commodity to be managed to meet established quantity and quality criteria. Water is a living resource. One challenge for ecologists is to use that fact to develop better ecological indicators of water quality that rely on the living communities of water to provide information on the ecological integrity of the aquatic ecosystem. One such index based on fish communities in running waters has been successfully used in North America (Karr, 1991). More such indices are needed based on different taxa and different ecological attributes of the system. The water manager needs a palette of available ecological indices from which to choose. This offers a direct research challenge to the community of ecologists.

A final research challenge for ecologists is provided by the need to restore aquatic ecosystems, so well documented by the recent WSTB report Restoration of Aquatic Ecosystems (NRC, 1992). As human assaults on natural systems have accelerated over the past decade, so has the need for a more holistic concept of system management that has the goal of maintaining and restoring the ecological integrity of the resource rather than simply preserving water quantity or quality. Restoration offers exciting challenges to ecologists by providing a real-world testing of ecological theories on how ecosystems are structured. Restoration of damaged ecosystems based on sound ecological principles is really one part of a larger discipline, ecological engineering. Its practitioners seek to use insight from applied and theoretical ecological studies to develop self-designing and self-sustaining ecosystems to solve environmental problems (Mitch and Jorgensen, 1989). These ecosystems are supported by solar energy and require lower inputs of nonrenewable resources. Understanding gained from this work should stimulate further developments in the fundamental ecological sciences. Examples of this approach include use of wetlands to treat acid mine drainage or wastewater and use of water hyacinth beds or a *Phragmites*-filled lagoon to treat wastewater (case studies in Mitch and Jorgensen, 1989). In several of these examples a useful product (e.g., water hyacinth for forage) is harvested from the engineered ecosystem, making it economically more appealing. Fundamental ecological research is needed for optimal construction, biotic composition, and operation of such engineered ecosystems. A greater emphasis needs to be placed on the use of native species instead of relying on imported exotics that pose a threat if they escape.

In this paper I have discussed some management implications of advances in ecological thinking with respect to the balance of nature and the importance of indirect effects. A third development that bears mentioning in conclusion is recognition of the global nature of ecological science. The human species currently uses, coopts, or destroys nearly 40 percent of the terrestrial net primary productivity of the planet (Vitousek et al., 1986). We have altered the hydrologic cycle as well as cycles of most elements; human activities seem to be affecting climate; biodiversity is declining rapidly. Events such as these require scientists and managers alike to think on a global scale. In one sense or another, we all live downstream.

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7

The Water Science and Technology Board: A Success Story of a Run Down the Rapids of Science Policy

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MULTIPLE PARADIGM SHIFT RAPIDS

This symposium celebrates the first decade of the Water Science and Technology Board's (WSTB) existence by looking back to the future. There are many aspects of the WSTB's impressive and extensive work that can be justifiably celebrated: the reputation that it enjoys in the water community, the level of output, the capable and professional staff, and the increased level of project funding (NRC, 1991a). These are important reasons for celebration, but the most important is the WSTB's willingness to reflect critically on its mission and to define a future role for itself that confronts some of the most difficult current questions of science and science policy related to water resources management.

All scientific research and application operate in a rapidly changing scientific and cultural environment, but the degree of change for water professionals is especially rapid. Hydrologists, environmental scientists, and engineers face substantial internal and external pressures about the future of their disciplines. As the WSTB's report Opportunities in the Hydrologic Sciences (NRC, 1991b) notes, the boundaries of hydrology, and thus its complexity and uncertainty, are expanding. To complicate matters further, scientific understanding must be integrated into a complex, rapidly changing institutional framework.

The WSTB has, in my limited National Research Council (NRC) experience, been unusually introspective. The NRC's model of science advice, which stems from its emergence as the government's science adviser between 1916 and 1918, is a committee of experts thrown together for a relatively brief period of time to formulate a consensus on the state of the art of a given problem (Oleson and Voss, 1980). This model is not conducive to introspection, in part because it reflects the NRC's long tradition of defining what is science and thus scientific issues narrowly. However, the WSTB has tried to overcome these constraints by developing a broad multidisciplinary framework for the integration of its separate studies. It has developed a set of strategic plans and a Terms of Reference, which allows the WSTB both to respond to specific client requests and to exercise control over its agenda. Through self-education and a strong stable staff with an institutional memory, the WSTB has tried to abstract general problems and lessons from its specific studies and apply these to new studies so that its experience and learning will be progressive as its composition changes.

The proactive, forward-looking posture of the WSTB represents an attempt to confront three related fundamental shifts in the organizing principles of water resources engineering, hydrology, and related relevant physical and social sciences. Our view of nature and role of human intervention in it has changed. The role of water resource management institutions is changing from development to management. Finally, the ethic of immediate consumption, which has guided natural resources policy, is changing.

These shifts undermine the assumptions about water resources management that were put in place at the turn of the century during the progressive conservation era and were applied throughout the first six decades of this century (Reuss, 1992). In brief, from the turn of the century through the 1960s, it was assumed that large-scale multipurpose water resources projects were essential to the economic well-being of the nation and that water management meant planning and operating these projects to maximize four primary uses—irrigation, hydropower generation, municipal and industrial supply, and flood control; recreation was a late and secondary add-on. This assumption eroded in the face of the environmental movement (Feldman, 1991). The result is that we now rely less on permanent structural solutions and more on adaptive management of existing physical and seminatural systems.

RAPID MILEPOST ONE: UNBALANCED NATURE

The first shift is our changed perception of the function of human manipulation of nature. During most of this century, the object of water resources engineering and hydrology was the rational manipulation of nature. Students of water resources management have assumed that accurate hydrologic data existed to explain river system behavior for water management, if only decision makers would heed the information. The environmental movement initially changed the focus from the manipulation of nature to its conservation or preservation. The WSTB's work reflects both the legacy of the heroic period of water resources engineering and the postheroic period. Its work in flood forecasting, Estimating Probabilities of Extreme Floods: Methods and Recommended Research (NRC, 1988), and dam safety, Safety of Dams: Flood and Earthquake Criteria (NRC, 1985) and Safety of Existing Dams: Evaluation and Improvement (NRC, 1983), reflects this distinguished twentieth-century tradition. However, much of the WSTB's work in groundwater remediation, irrigation drainage, and coastal and estuarine water management reflects the postheroic tradition. This new era has posed acute problems for the WSTB because the problems brought to it challenge the historic assumption, on which much of the NRC's work is based, that it is possible to assemble preexisting, sound, scientific information on which to base decisions. In many cases this is not true for reasons that go to the organization of the underlying science and the increased societal expectations for science.

The WSTB has had to operate under three major constraints that reflect the changing environment of science. First, water science is not high-priority science because it does not directly serve military or foreign policy, including trade objectives (Dickson, 1988). Second, it has to operate in the post-1960s scientific environment. Science must now meet two standards: it must be relevant to larger social issues, and it must be accountable. Third, as a result of these first two constraints, it must offer credible advice on questions that are not often on the research agendas of the primary producers of knowledge.

These changes stress the traditional NRC process of rendering science advice. The National Academy of Sciences/National Research Council was created to render consensus scientific and technological advice to the federal government. The model is a committee of national or international experts who survey a field and issue a report that resolves a debate within a discipline about a specific, narrow "scientific" question. Under this model, the principal political problem for scientists is ensuring that the right people listen to them and take the proper actions. The literature on science policy has documented failures to listen and speculated about how to prevent them. This model began to break down in the environmental era when scientists were asked to pronounce on issues with high ranges of uncertainty.

In the 1970s the federal government began to enact laws to prevent unsafe levels of exposure to toxic chemicals by mandated risk assessments. Risk assessments call for information on the frontiers of science; thus, the level of information required to make a decision based on the consequences of exposure to a toxic substance is never available and is not likely to ever be available within a reasonable time span or at a reasonable cost. The federal government first enacted laws to control gross forms of air and water pollution, but, after the DDT controversy, cancer risk became a proxy for almost all environmental health risks. The net result was that the line between scientific inference and the more rigorous legal standard of proof of cause began to blur as all regulatory decisions had to be made under conditions of extreme uncertainty.

The newly created Environmental Protection Agency was asked to regulate the use of toxic substances to minimize their long-term risks. Science has always been contingent, but the necessity to justify risk assessments exposed the high level of contingency. Initially, the NRC tried to use the consensus approach to resolve these issues. The hope was that good science would provide objective criteria to make regulatory decisions about issues such as toxic risks. We now realize that there are two problems with the "good versus bad" science model. First, good science is a political construct that has too often been used to deflect hard questions about the social costs of technology. But there is a second and more profound problem that is not a function of abused or sloppy science. Good science, defined as elegant hypothesis construction and testing, is often inadequate to provide the necessary information and thus the rational guidance for scientifically sound decision making.

There are several reasons for this, but the fundamental one is that good science does not always equal good regulatory science. In the science policy literature the relationship between regulation and science has been explored at great length but from a different perspective than I wish to emphasize. There are many documented cases of the subordination of science to regulatory objectives (Jasanoff, 1990). The usual complaint by scientists and students of science policy is that policy makers do not listen to scientists because their advice undermines the political objectives of a program that the policy makers wish to pursue for other objectives. "Communication" between scientific experts and policy makers is an important and continuing problem for the science community and the WSTB. But the WSTB's studies reveal a deeper problem with laudable efforts to enlist science to serve public purposes such as environmental protection.

The WSTB's work in such diverse areas as environmental monitoring, reservoir management, and aquatic restoration illustrates the limits of good science; the relevant disciplines are being asked to answer questions that have not been on the conventional research agenda. The basic problem is that many modern water resources management decisions require scientific baselines of <u>altered</u> environments against which existing and contemplated human intervention can be evaluated. Science is increasingly criticized not because it is bad but because it is irrelevant or inadequate to answer questions. There are two fundamental reasons for the difficulties of applying science to the issues brought to the WSTB for resolution. The first reason is that the questions are framed as scientific questions when they are in fact scientifically informed value judgments. Scientists are increasingly being pushed to give answers to questions that are framed as positive or verifiable but that are in fact normative because a decision must be made before acceptable verification procedures can be followed.

These new problems of scientific uncertainty reflect the revised view of nature that informs much scientific research. Many of the scientific dilemmas facing the WSTB support the thesis in Daniel B. Botkin's book (1990), Discordant Harmonies: A New Ecology for the Twenty-First Century. Botkin's basic argument is that the images of nature that have influenced ecology are static when in fact the kinds of problems that we face require a dynamic view of nature. The accelerating interaction between humans and the natural environment makes it impossible to return to an ideal state of nature. At best, it can be managed rather than restored or preserved, and management will be a series of calculated and risky experiments. "[N]ature moves and changes and involves risks and uncertainties and ... our own judgments of our actions must be made against this moving target" (Botkin, 1990). Judy L. Meyer's paper, "Changing Concepts of System Management," details the evolution of the nonequilibrium paradigm and its implications for the WSTB's work.

RAPID MILEPOST TWO: MANAGING RATHER THAN POURING CONCRETE

The WSTB is also caught in a new social paradigm shift. Since the progressive conservation era, the river basin has been the organizing unit for water resources planning and management. Historically, the objective of water management was the development of a coordinated system of multiple-purpose reservoirs and associated water projects on all major river basins (Graf, 1992). The idea of river basin development has been replaced with a more amorphous idea of river system management for a variety of social objectives; the most fundamental change is the idea that human uses of water resources and environmental protection and management should be given equal weight (Feldman, 1991).

Several WSTB recent studies, Restoration of Aquatic Ecosystems (NRC, 1992) and the publications of the continuing Committee to Review the Glen Canyon Environmental Studies, illustrate the complexities of new management and the scientific problems that it poses. These studies recommend the creation of holistic management processes that constantly acquire and evaluate new scientific information through what are essentially management experiments rather than solutions.

RAPID MILEPOST THREE: THE NEW ETHIC OF SUSTAINABILITY

The ultimate challenge for future resource managers will be to integrate science, technology, and institutions into a new ethical perspective. Again, the WSTB is a model of the integration of ethical perspectives into science-based resource management. The WSTB's first Abel Wolman lecturer, Luna Leopold, addressed the ethical dimension with his plea for the recognition of an "ethos of long-term sustainability" (Leopold, 1990), but the tradition of the incorporation of ethical perspectives and the emphasis of long-term sustainability go back to the inception of the WSTB.

The WSTB's studies are distinguished by efforts to include a discussion of the ethical dimensions of the scientific information being assembled and assessed. The foundation of any water ethic is the same as the foundation of environmental ethics: the incorporation of the interests of future generations into present resource allocation. The WSTB was fortunate to have the services of Professor Edith Brown Weiss from 1986 to 1988. During her service, Weiss formulated her theory of justice between generations that is now the organizing principle of international environmental protection initiatives (Weiss, 1989). The WSTB's report The Great Lakes Water Quality Agreement: An Evolving Instrument for Ecosystem Management (U.S. National Research Council and Royal Society of Canada, 1985) was the first major Academy report to urge the adoption of this ethical perspective, and Weiss's theories continue to influence the WSTB's work. For example, Weiss participated in the Bureau of Reclamation's colloquium that led to the report Managing Water Resources in the West Under Conditions of Climate Uncertainty (NRC, 1991c), and in 1991 a leading historian of environmental ethics, Professor Roderick Nash, was appointed to the Glen Canyon Environmental Studies Committee to bring perspectives on intergenerational equity explicitly before the committee.

Weiss's symposium paper, "Intergenerational Fairness and Water Resources," demonstrates that most of the WSTB's work deals with intergenerational equity issues. The challenge for the future will be twofold: (1) it is important to make the ethical issues explicit from the beginning of a WSTB activity, and (2) WSTB studies must seek innovative methods to implement intergenerational equity by suggesting effective, scientifically credible sustainability strategies.

A LOOK AT FUTURE CANYONS AND RAPIDS

The WSTB has become a successful and sustainable unit of the National Academy of Sciences. Parts of its success is that it has been able to build on past studies and integrate its studies into progressively larger and more general frameworks. In general, its studies focus on sets of recurring themes that should hold for the foreseeable future. It is impossible to predict the nation's future water agenda, but I think it is a conservative prediction that for the foreseeable future the WSTB's work will expand on the following four areas:

1. <u>Allocation of scarce water resources</u>. The competition for water resources is becoming more intense. Our traditional allocation strategies, such as supply augmentation through dams and subsidies, are under great stress because they do not reflect the full range of relevant demands and social values. The WSTB has explored and continues to explore the acute allocation problems in the West, but its work is fully national in scope, as its investigations of such issues as urban water supply management and the reclamation and reuse of wastewater illustrate.
2. <u>Adaptive management and monitoring</u>. A continuing and pervasive theme in the WSTB's work is the difficulty of applying good science to the modern management of natural resources for the worldwide goal of biodiversity protection. There are both institutional and disciplinary barriers that make it difficult to use science information effectively to solve the range of modern management problems, such an environmental monitoring, reservoir system management, or aquatic systems. The need to make decisions in the face of scientific uncertainty is now a familiar management principle, but there is also a need to ask why the uncertainty arises and whether and how it can be minimized and to provide a range of appropriate responses to these problems.
3. <u>Ground water</u>. The WSTB has developed considerable credibility with its studies on ground water hydrology and ground water management, and this tradition will serve it well in the future as the use of this resource increases. The WSTB's work on the technical aspects of ground water models that can be used to aid in aquifer cleanups and other management issues is a model of the role that the WSTB can play in applying science to solving regulation-driven problems.

4. Application of U.S. experience to other countries. The United States has had long and varied experiences, with almost all controversial water resources issues. We have much to learn from other countries, both developed and developing, but we also have a great deal of information and experience to share with the rest of world. Increased attention to international, comparative, and developing-country studies is a logical extension of the WSTB's first decade. There is a good tradition on which to build.

The WSTB has carried out an important joint study with Canada, The Great Lakes Water Quality Agreement: An Evolving Instrument for EcosYstem Management (U.S. National Research Council and Royal Society of Canada, 1985); has written a useful report, Toward Sustainability: Soil and Water Research Priorities for Developing Countries (NRC, 1991d), on the integration of sustainable development concepts into U.S. support of soil and water research in developing countries; and in 1991–1992 began a major study with the Mexican Academy of Sciences on the management of Mexico City's aquifer. Also, in 1992 in cooperation with the Board on Science and Technology for International Development, the WSTB staff aided the government of Indonesia's academy of sciences in the design and organization of a major water resources study.

As environmental problems become a larger part of our international affairs agenda, the WSTB can play an important role in facilitating the international exchange of water resources management information. It should be represented at major international meetings on issues such as drought management, global climate change, irrigation and urban water supply; it should pursue joint studies with countries whose geography and resource allocation patterns and problems match those of the United States; and it should seek to integrate its efforts with major international agencies such as the World Bank, working on such issues as urban water supply and sanitation and the development of sustainable irrigated agriculture as a replacement for large multiple-purpose projects. And, wherever relevant, its studies should include a comparative context to alert scientists, managers, and scholars to the international dimensions of the issue.

The ability to adapt to new knowledge is the hallmark of successful management, and it is a necessary condition for water management as we move from an era of rapid exploitation to one of sustainable use. The WSTB's tradition of introspection and self-education has enabled it to become a respected, forceful, and objective voice in the water community. This tradition will serve it well as it continues to grapple with the increasingly difficult problems of both nurturing the relevant engineering, natural, and social sciences necessary for adaptive water management and applying science to the laudable but difficult goal of achieving sustainable use.

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Appendixes

Appendix A

Symposium Program

November 9, 1992
National Academy of Sciences Auditorium

1:00 p.m.	Opening Remarks
1:10 p.m.	Welcome, **Stephen D. Parker, Director, Water Science and Technology Board**
1:20 p.m.	Introductions, **Daniel A. Okun, University of North Carolina, Chapel Hill**
1:25 p.m.	Keynote, Intergenerational Equity, **Edith Brown Weiss, Georgetown, University Law Center**
1:45 p.m.	Discussant, **Stephen Rattien, Executive Director, Commission on Geosciences, Environment, and Resources;** audience dialogue
2:00 p.m.	Landscapes, Commodities, and Ecosystems: The Relationship Between Policy and Science for American Rivers, **William Graf, Arizona State University, Tempe**
2:20 p.m.	Discussant, **Wilford R. Gardner, University of California, Berkeley;** audience dialogue
2:35 p.m.	Changing Knowledge Base: Keeping Pace with Changing Values and Perceptions , **George M. Hornberger, University of Virginia**

2:55 p.m. Discussant, **David L. Freyberg, Stanford University;** audience dialogue

3:10 p.m. BREAK

3:30 p.m. Changing Patterns of Water Resources Decision Making, **Walter R. Lynn, Cornell University**

3:50 p.m. Discussant, **Charles C, Johnson, private consultant, Bethesda, Maryland;** audience dialogue

4:05 p.m. Changing Institutions, **Kenneth D. Frederick, Resources for the Future**

4:25 p.m. Discussant, **John J. Boland, The Johns Hopkins University;** audience dialogue

4:40 p.m. Changing Concepts of System Management, **Judy L. Meyer, University of Georgia**

5:00 p.m. Discussant, **Kenneth W. Potter, University of Wisconsin-Madison;** audience dialogue

5:15 p.m. Looking Back and Ahead: The WSTB's Future Agenda, **A. Dan Tarlock, IIT Chicago Kent College of Law**

5:35 p.m. Discussant, **Daniel A. Okun, University of North Carolina, Chapel Hill;** audience dialogue

5:50 p.m. Closing Remarks, **Daniel A. Okun, University of North Carolina, Chapel Hill**

6:00 p.m. Reception, Great Hall

Appendix B

Biographical Sketches of Authors

Kenneth D. Frederick holds a Ph.D. in economics from the Massachusetts Institute of Technology. He has been a senior fellow at Resources for the Future since 1971. Previously, he was on the faculty of the California Institute of Technology and has held various consulting positions. Dr. Frederick has produced over 50 publications of various types on natural resources policy issues. In recent years his research has concentrated on policy aspects of climate change and various water management issues. He is a member of the Water Science and Technology Board and is also a member of its recently completed Committee on Climate Change and Water Resources Management.

William L. Graf is a geomorphologist specializing in river mechanics, with a secondary interest in public land and water policy. He is professor of geography at Arizona State University. His B.A., M.Sc. (with certificate in water resources management), and Ph.D. in geography are from the University of Wisconsin-Madison. He has published five books, including volumes on the Colorado River, geomorphic systems of North America (edited for the Geological Society of America), dryland river processes, and American public land management. He has published more than 50 scientific papers and an additional 50 research reports and related pieces, mostly focusing on rivers in the western United States. He has served as an expert witness in nearly 20 legal cases and has advised the National Park Service on river management in several western parks. His research has emphasized the analysis of river channel change under the influences of climatic adjustments and human intervention, with his most recent work focusing on the problems of heavy metal and radionuclide transport in river systems. Grants from the National Science Foundation, Environmental Protection Agency, Army Corps of Engineers, Los Alamos National Laboratory, Department of the Interior, Department of Justice, and National Geographic Society have supported his work. Dr. Graf has received the G. K. Gilbert Award for Excellence in Geomorphological Research, the 1990 Honors Award from the Association of American Geographers, and the Cole Memorial Award for Arid Region Research from the Geological Society of America. He is a member of the Water Science and Technology Board and is also a member of its Glen Canyon Environmental Studies Committee since its inception in 1986.

George M. Hornberger obtained his Ph.D. in hydrology from Stanford University in 1970. He also holds a bachelor's degree (1965) and a master's (1967) degree in civil engineering from Drexel University. He is a professor in the Department of Environmental Sciences at the University of Virginia. He is currently interested in modeling environmental systems with uncertainty, the hydrogeochemical response of small catchments, and the transport of bacteria in porous media. He is also chairman of the Water Science and Technology Board's Committee on Water Resources Research.

Walter R. Lynn received a Ph.D. from Northwestern University in 1963 and is an expert in environmental systems engineering. He is currently dean of the faculty and professor of civil and environmental engineering at Cornell University. Dr. Lynn has served on several NAE and NRC committees, boards, and panels and was the Water Science and Technology Board's first chairman (1982–1985). He now chairs the NRC's Board on Natural Disasters.

Judy L. Meyer is professor of limnology and ecology at the University of Georgia. She received her Ph.D. in ecology from Cornell University. From 1970 to 1972 she was a research associate in the Oceanography Department at the University of Hawaii, and from 1977 to 1983 she was an assistant professor of zoology at the University of Georgia. She is currently professor of zoology at the University of Georgia. Her research interests are in aquatic ecology, terrestrial-aquatic ecology, terrestrial-aquatic ecosystem interactions, dissolved organic carbon in streams, blackwater rivers, and microbial food webs in streams. Dr. Meyer is a member of the Water Science and Technology Board and was a member of its former Committee to Review the USGS National Water Quality Assessment Pilot Program.

A. Dan Tarlock received his LL.B. from Stanford University. His professional experience includes private practice, San Francisco, 1966; professor-in-residence at a law firm in Nebraska during the summers of 1977 to 1979; and consultant. He has been a professor of law at Chicago Kent College of Law since 1981. He has authored and coauthored many publications and articles concerning water resources management and environmental law and policy. Mr. Tarlock served as a member of the NRC Committee on Pest Management and is currently the vice chair of the Water Science and Technology Board. He also serves on the board's Glen Canyon Environmental Studies Committee and was chairman of the Committee on Western Water Management. He also coauthored one of the basic casebooks in water law.

Edith Brown Weiss is a professor of law at Georgetown University Law Center, where she has taught international law, international environmental law, water law, and environmental law. She recently finished a sabbatical at the U.S. Environmental Protection Agency, where she served as associate general counsel for international activities. Dr. Weiss has served as chair of the Social Science Research Council's Committee on Research in Global Environmental Change and is former vice president of the American Society of International Law. Dr. Weiss was a member of the Water Science and Technology Board from 1985 to 1988 and has served on several NRC committees. She is a member of the Board of Editors of the American Journal of International Law, International Legal Materials, and Climate Change Digest and was elected to membership in the Council on Foreign Relations, American Law Institute, and the International council on Environmental Law. Her book, *In Fairness to Future Generations*, received the Certificate of Merit from the American Society of International Law in 1990. She received her A.B. from Stanford University, LL.B. from Harvard Law School, and her Ph.D. from the University of California at Berkeley. She is also a member of the NRC's Commission on Geosciences, Environment, and Resources.

Appendix C

WSTB Publications

Publication	Available from
Water Science and Technology Board Annual Report, 1988, 1989, 1990, 1991, 1992–1993	Water Science and Technology Board
Managing Wastewater in Coastal Urban Areas, 1993	National Academy Press
Ground Water Vulnerability Assessment: Predicting Contamination Potential Under Conditions of Uncertainty, 1993	National Academy Press
Regional Hydrology and the USGS Stream Gaging Network, 1992	National Academy Press
A Review of Ground Water Modeling Needs for the U.S. Army, 1992	Water Science and Technology Board
The Global Climate Change Response Program: A Mid-Course Evaluation, 1992	Water Science and Technology Board
Restoration of Aquatic Ecosystems: Science, Technology, and Public Policy, 1992	National Academy Press

Publication	Available from
Water Transfers in the West: Efficiency, Equity, and the Environment, 1992	National Academy Press
Glen Canyon Environmental Studies Letter Reports, 1992	Water Science and Technology Board
Review of EPA's Environmental Monitoring and Assessment Program, Interim Report, 1992	Water Science and Technology Board and Board on Environmental Studies and Toxicology
Review of the National Irrigation Water Quality Program—Part I & II, 1991 and 1992	Water Science and Technology Board
Opportunities in the Hydrologic Sciences, 1991	National Academy Press
Preparing for the Twenty-First Century: A Report to the USGS Water Resources Division, 1991	National Academy Press
Toward Sustainability: Soil and Water Research Priorities for Developing Countries, 1991	National Academy Press
Review of the Draft Integrated Research Plan for the Glen Canyon Environmental Studies, Phase II, 1991	Water Science and Technology Board
Colorado River Ecology and Dam Management, 1991	Water Science and Technology Board
Managing Water Resources in the West Water Under Conditions of Climate Uncertainty, 1991	Water Science and Technology Board
Ground Water Models: Science and Regulatory Applications, 1990	National Academy Press
Managing Coastal Erosion, 1990	National Academy Press

Publication	Available from
A Review of the U.S.G.S. National Water Quality Assessment Pilot Program, 1990	National Academy Press
Surface Coal Mining Effects on Ground Water Recharge, 1990	National Academy Press
Ground Water and Soil Contamination Remediation: Toward Compatible Science, Policy, and Public Perception, 1990	National Academy Press
Irrigation-Induced Water Quality Problems: What Can Be Learned from the San Joaquin Valley Experience? 1989	National Academy Press
Great Lakes Water Levels: Shoreline Dilemmas, 1989	National Technical Information Service
National Water Quality Monitoring and Assessment Interim Report, 1989	Water Science and Technology Board
Estimating Probabilities of Extreme Floods: Methods and Recommended Research, 1988	National Technical Information Service
River and Dam Management: A Review of the Bureau of Reclamation's Glen Canyon Environmental Studies, 1988	Water Science and Technology Board
Glen Canyon Environmental Studies Supplemental Letter Report, 1988	Water Science and Technology Board
Hazardous Waste Site Management: Water Quality Issues, 1988	National Academy Press
National Water Quality Monitoring and Assessment, 1987	National Technical Information Service

Publication	Available from
Ground Water Quality Protection: State and Local Strategies, 1986	National Academy Press
A Review of the U.S. Army Construction Engineering Research Laboratory Program for Recycling and Reuse of Laundry and Shower Wastewater, 1986	National Technical Information Service
Drought Management and Its Impact on Public Water Systems, 1986	National Academy Press
The Great Lakes Water Quality Agreement: An Evolving Instrument for Ecosystem Management, 1985	National Technical Information Service
Safety of Dams: Flood and Earthquake Criteria, 1985	National Academy Press
The Lake Erie—Niagara River Ice Boom: Information Operations and Impacts, 1984	National Technical Service
The Potomac Estuary Experimental Water Information Treatment Plant, 1984	National Technical Service
Water for the Future of the Nation's Capital Area, 1984	National Technical Information Service
Review of the Great Lakes Water Quality Agreement: Working Papers and Discussion, 1984	National Technical Information Service
Safety of Existing Dams: Evaluation and Improvement, 1983	National Academy Press
Cooperation in Urban Water Management: Information Conference Proceedings, 1983	National Technical Service
A Levee Policy for the National Flood Information Insurance Program, 1982	National Technical Service

Publication	Available from
Safety of Nonfederal Dams: A Review of the Federal Role, 1982	National Technical Information Service

The addresses of the three sources are as follows:

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