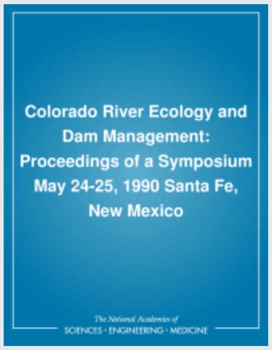

Colorado River Ecology and Dam Management: Proceedings of a Symposium May 24-25, 1990 Santa Fe, New Mexico

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Colorado River Ecology and Dam Management

Proceedings of a Symposium May 24–25, 1990 Santa Fe, New Mexico

Committee to Review the Glen Canyon Environmental Studies
Water Science and Technology Board
Commission on Geosciences, Environment, and Resources

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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On the walls, and back many miles into the country, numbers of monument-shaped buttes are observed. So we have a curious ensemble of wonderful features—carved walls, royal arches, glens, alcove gulches, mounds, and monuments. From which of these features shall we select a name? We decided to call it "Glen Canyon".

From John Wesley Powell's 1869 Expedition

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* Although Dr. Hanemann gave a presentation discussing the economics of hydropower operations, he did not deliver a written paper for this proceedings.

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Acknowledgments

Thanking the many people who contributed to the success of this symposium carries the risk of embarrassing omissions. The need for special thanks is obvious, however, and so I hope that any omissions will be forgiven. Professor Luna B. Leopold patiently absorbed the symposium discussions from the front row and was kind enough to make cogent concluding remarks. Sheila David has been the Water Science and Technology Board (WSTB) staff officer for this committee activity from the beginning in 1986. She has kept us organized and on time, and has carried many frustrating burdens for us when we needed help. Renee Hawkins and Chris Elfring, also of the WSTB staff, kept the details of the organization of this meeting from being known to anyone. It was that smoothly done.

We of course owe our gratitude to the authors who delivered these papers, but also to the people asked to participate in panel discussions that contributed structure to the open discussions. The committee acknowledges that the success of the symposium was due in large measure to their interest and enthusiastic discussion of the many issues surrounding protection of the environment in the Grand Canyon.

G. RICAHRD MARZOLF

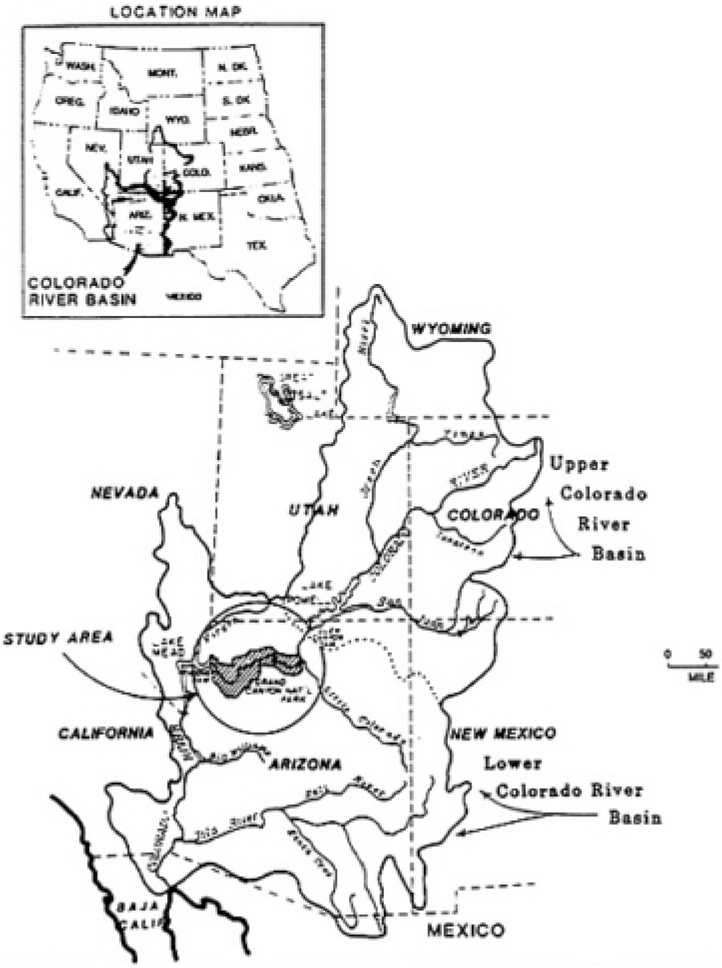
CHAIRMAN

COMMITTEE ON GLEN CANYON ENVIRONMENTAL STUDIES

Committee Synopsis

In July 1986, the U.S. Bureau of Reclamation (USBR) asked a National Research Council (NRC) committee to help evaluate their environmental studies being conducted on the lower Colorado River and to provide advice on alternative operations of the Glen Canyon Dam. Glen Canyon Dam, completed in 1964, is one of several high-head, multipurpose storage projects in the Colorado River system (see map). For more than 30 years issues concerning the effect of dam operations on the natural resources of the Grand Canyon National Park have been raised. The USBR's Glen Canyon Environmental Studies (GCES) were intended to evaluate the relationships between dam operations and the natural resources of the Grand Canyon. Based on these analyses, modified reservoir operating policies were to be considered.

It may be useful for the reader to refer to a previously issued committee report, *River and Dam Management: A Review of the Bureau of Reclamation's Glen Canyon Environmental Studies* (NRC, 1987) to assist in understanding the scope of GCES issues and the NRC's involvement in providing advice to the Bureau of Reclamation. In its 1987 report, the committee found that the GCES gave insufficient attention to early planning and to careful articulation of GCES objectives and that it inadequately considered management options. The NRC report also noted that recommended management options made by the Bureau of Reclamation were not supported by the GCES research results and that researchers had failed to identify the rationale for



Location map of the Colorado River basin.
SOURCE: U.S. Department of the Interior, 1987.

assigning values to downstream resources so that management goals could be set. The USBR's report, issued in 1987 (U.S. Department of the Interior, 1987), recommended several management options. The NRC committee stated that, of those, only the recommendations that called for continued study of dam operations and nonoperations alternatives, along with additional research and monitoring of the Colorado River, were justified.

Since 1987, a reorganized committee has worked with the USBR's GCES program manager and GCES researchers to help implement many of the recommendations in the NRC's 1987 report. One of that report's findings suggested that the results of the GCES (U.S. Department of the Interior, 1987) represented a substantial increase in knowledge of the Colorado River ecosystem as it exists in the Glen Canyon and the Grand Canyon. Existing historical information had not been fully reviewed at the beginning of the GCES. This finding led to the committee's criticism that in the GCES too much of the existing information had been ignored in the planning stages of the research. As a result of the varying agency budgets, missions, and pools of researchers, the planning process for the GCES did not treat the ecosystem components as part of a whole. Had the researchers been given the time and funds to review the extant literature about the Colorado River ecosystem, the committee believes they would have recognized at a much earlier stage, the need to address interaction of ecosystem components.

The NRC committee recommended that a review of existing knowledge precede future investigations. The review should be an early step in the planning phase and should result in the preparation of written documentation. The USBR began Phase II of the GCES (GCES II) in 1988. In 1989 the Secretary of the Department of the Interior ordered that an environmental impact statement (EIS) be developed and that the GCES II results be incorporated into the EIS. The NRC committee was asked to continue providing advice to the GCES and to help by reviewing the existing knowledge about the Colorado River ecosystem in the Grand Canyon. To undertake that task, the NRC sponsored a symposium in May 1989 in Santa Fe, New Mexico, entitled "Colorado River Ecology and Dam Management." These proceedings document that event.

Approximately 200 people attended the symposium. Eleven invited papers were prepared to (1) review extant information about the river from an ecosystem perspective and (2) serve as the basis for discussions on the use of ecosystem/earth science information for river management, and dam operations.

The report has two sections: the committee's findings and recommendations, and background papers presented at the symposium. The findings and recommendations integrate the steering committee's review of the background papers, the lively discussion at the symposium, and the committee's own judgements about USBR management of the Glen Canyon Environmental

Studies. The background papers contain the conclusions of individual authors, many but not all of which are reflected in the committee's synopsis.

The authors of the papers were chosen for their expertise and interest in the subject. The committee thanks them for their excellent work and timely response to the task set before them. As scholars from different backgrounds, they showed impressive skill in moving toward the integrated view that will be required to address the complex issues involving decisions about the operation of Glen Canyon Dam.

Most of the people who attended the symposium became active participants in the discussions. This is a measure of the importance that the subject has for busy people. The people with management responsibilities learned a bit more about how science can be useful to management; scientists learned more about the complex tasks of management. Policy decisions will be guided in new and productive directions if this alliance matures. By any measure, the meeting was stimulating; the committee hopes that this report will be a useful stimulus to future environmental research in the Grand Canyon.

The committee's findings and recommendations are directed to the USBR as it continues to grow in its role as a manager of the nation's natural resources.

FINDINGS AND RECOMMENDATIONS

Initiate Long-Term Research and Monitoring in the Grand Canyon

Since 1964, the operation of Glen Canyon Dam has caused continuing ecosystem changes in the Grand Canyon reach of the Colorado River. Some changes were immediate (e.g., decrease in water temperature, sediment load reductions, and flow regime alterations), but most others (e.g., geomorphic adjustment of the channel, secondary succession of terrestrial vegetation, and changing aquatic species composition) are occurring on longer time scales. Introduction of and invasions by exotic species are influencing the ecosystem as well.

Many of the changes caused by the construction of Glen Canyon Dam are irreversible, and so the Colorado River cannot be managed to reestablish the pre-dam conditions in the Grand Canyon. Because ecosystem components are linked to one another and to the flow regime imposed by the dam, the potential exists for manipulating the system, that is, manipulating flows to manage the river and protect the environment in the national park. The interaction between management and science can lead to the discovery of new knowledge and should be useful to management for monitoring the effectiveness of management performance. The achievement of this interaction will require the U.S. Bureau of Reclamation (USBR) to:

- ***Establish a mechanism to develop management goals for the Colorado River in the Grand Canyon National Park. Priorities for implementation can then be developed by a multi-disciplinary management team.***
- ***Initiate careful and intensive planning of long-term research needs and a long-term monitoring program to establish and refine ecological understanding in the Grand Canyon and to check the performance of management actions. This planning should involve the help of experienced people in all of the disciplines required. The National Research Council (NRC) committee recommended in 1987, and continues to recommend, that an advisory group be established at the secretarial level in the Department of the Interior (DOI) so that the varying agency missions will be less of a barrier to effective resource management.***
- ***Establish the management and monitoring program in the Grand Canyon as a long-term scientific investigation.***
- ***Integrate science into its management of natural resources. This "adaptive management" approach strives to balance the rigors of science with increasing requirements and constraints within the federal decision-making process.***

Ensure that Dam Operations Are Flexible

The complicated interactions of (1) the economics of hydropower generation and marketing and (2) the management of natural resources are not well understood. The legal requirements for dam operations to meet water allocations required by the Colorado River Compact are not a strong constraint on alternative operations of Glen Canyon Dam.

- ***The USBR and the Western Area Power Administration (WAPA) should integrate scientific investigation with the full range of power generation options possible within the law of the river to make rational management decisions.***
- ***More effective mechanisms should be sought to meld economic and operations research into ecosystem research. To be effective, this integration must be an on-going and flexible process.***

Manipulation of dam operations to achieve management goals should be implemented with the understanding that there is some uncertainty at this stage. This means that operating the dam to achieve management goals in the Grand Canyon will be, to some extent, experimental. The performance monitoring that follows implementation will be the data collection phase of long-term experiments. Corrections can be made as the system becomes better known.

Issues include:

- Estimating economic costs of increased minimum releases, using hourly historic data for developing generation and load probability distributions.
- Estimating costs of various ramping rates between peak and off-peak hours.
- Economic costs of various marketing policies of WAPA.
- The changes in the energy load of the Colorado River Storage Project in the short and long terms.

Seek Research Talent from the Academic Sector

When seeking scientific leadership in 1988–1989 for the GCES II, the USBR published a request for proposals (RFP) that emphasized schedules and deliverable products rather than documentation of the skills and scientific records of the principal investigators. Thus, the RFP failed to attract the sort of experienced scientist required for the planning and development of GCES II.

A later search process was more effective because it specified the need for a person with scientific knowledge and specific skills and experience to do the planning and to guide the selection of scientists who would perform the high-quality research that the USBR expects. However, a search for researchers in the summer of 1990 reverted to use of the RFP process that had fallen short before (i.e., RFPs sent with preference given to small businesses).

Because the scientific talent to accomplish these tasks was not found in the small-business sector, the committee believes that this particular process is less likely to attract people with the collection of skills, talents, and experience that will serve the project best. To succeed, this work requires highly motivated and creative talent. The GCES needs qualified and talented scientists to perform the research required. Therefore, the committee believes the search for this talent should be widespread and should include the academic sector as well as others.

- ***After implementing the long-term monitoring program, the USBR should initiate a broad search for proposals, including proposals from the academic sector, to find answers to general questions about the Colorado River ecosystem in the Grand Canyon and about its responses to the operation of Glen Canyon Dam. Proposals should include background review, clear statements of work objectives and approaches to achieving them, specific schedules, budgets, and full documentation of the talents and experience of the investigators***.
- ***The USBR should ensure that these proposals are then reviewed on a competitive basis by a panel of peer scientists for incorporation into the long-term GCES program***.

- ***The USBR should plan to carry out short-term investigations selected by this process in concert with long-term monitoring. The long-term monitoring provides documentation of the status of the system when the short-term work is performed.***

The long-term record will aid interpretation of the results. The results of short-term experimental work yield information about causes and effects that cannot be extracted from long-term time series data. Such results are useful because knowledge of cause-and-effect relationships is essential for the development of management manipulation plans (hypotheses). This recommended interaction of long-term monitoring and short-term experimental and theoretical work, thus, will be a powerful management combination.

Include the USGS on the Federal Executive Management Committee

A new committee, the Federal Executive Management Committee, has been appointed by the USBR to oversee the research associated with Glen Canyon Dam. This committee has representatives from the USBR, the National Park Service, the U.S. Fish and Wildlife Service, the Bureau of Indian Affairs, WAPA, and the Arizona Game and Fish Commission.

When questioned about the omission of the U.S. Geological Survey (USGS), the USBR pointed out that the USGS had no management mission and, in their opinion, no role on the Federal Executive Management Committee. The USGS has had an ongoing involvement with the research studies for the GCES and the committee believes their research and data-gathering experience will provide a useful perspective to the integration of research and management.

• ***Therefore, the USGS should be included on the Federal Executive Management Committee.***

Use an Ecosystem Approach to Grand Canyon Research

A major objective of the NRC symposium was a review of current information in the scholarly literature about the Colorado River ecosystem. This review revealed that many events in the history of human involvement in the development of this resource have occurred in isolation from one another, that is, without regard for their effects on other aspects of the ecosystem.

• ***The USBR should conduct future GCES research in the Grand Canyon using an ecosystem perspective to avoid the isolated implementation that has created problems in the past.***

Examples of effects resulting from the previous limited perspective of the GCES are as follows:

- ***Sediment transport records in the Grand Canyon were terminated in the mid-1960s.***
- ***Exotic species (invertebrates, fishes, and phreatophytes) were introduced.***
- ***Thus, the committee recommends a ban on the introduction of new exotic species to Lake Powell until the effects of dam operation on river fish communities is better understood.***
- ***No provision was made for the temperature and flow requirements of now endangered species. (Previously, the law did not require such attention.)***
- ***Narrow geographic boundaries were set for GCES I such that assessment of water quality from Lake Powell was excluded.***

Because of planning shortfalls prior to GCES I (NRC, 1987), there are still major gaps in knowledge.

Better understanding is still needed on:

- Trophic structure of Glen Canyon Dam tailwaters and its relationship to phenomena in Lake Powell and flow regimes associated with dam operation.
- Detailed water budget for Lake Powell, including better estimates of bank storage, evaporation, and discharge from the Glen Canyon Dam.
- Requirements for the protection of endangered species.
- Magnitude and timing of sediment contributions from tributary sources.
- Depositional fate of tributary sediments and documentation of their chemical qualities.
- Flow conditions that deposit sand at the margins of the river (beaches), which are not understood in enough detail to suggest a management strategy that will build beaches.

The research needed to increase understanding of these topics is not trivial. Nevertheless, investment in developing the information will make management decisions wiser, more defensible, and more cost-effective in the long term.

Revisit 1987 NRC Recommendations on the GCES

Sound scientific information is critical to making informed decisions about the use of natural resources. The 1987 report of the NRC committee made recommendations that would strengthen the scientific information base for decisions about and management of Glen Canyon Dam based on the results of GCES. Few of those recommendations have been implemented except for the hiring of a senior scientist to advise the GCES researchers.

Even this recommendation falls short as the scientist was not hired at the recommended Department of the Interior level, but rather under the Bureau of Reclamation. Therefore,

• ***USBR management should review the December 1987 NRC report* River and Dam Management *for reconsideration of the applicability of those recommendations to GCES II*.**

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1

The Law and Politics of the Operation of Glen Canyon Dam

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INTRODUCTION

The construction and operation of Glen Canyon Dam on the Colorado River have detrimentally affected downstream resource values. These impacts are particularly acute because they threaten the ecological integrity of Grand Canyon National Park. It may be possible to mitigate some of these impacts by modifying the timing and pattern of reservoir releases, but this would require the Bureau of Reclamation and the Western Area Power Administration (WAPA) to alter the existing hydropower production regime. Proponents of the status quo sometimes argue that the law of the river prohibits any deviation from the present operation of the dam. This paper addresses the relationship between the law of the river and the day-to-day operation of Glen Canyon Dam.

We argue that the law of the river does not prohibit management changes to mitigate downstream resource value losses or to reflect other social values. The law of the river is a law of mass allocations between regions and among states which reflects a changing political balance among conflicting regional values. The rationale for water development decisions has always been multiple, including flood control, irrigation, water supply, economic development, recreation, and fish and wildlife habitat enhancement, as well as power generation. Power generation has never been a primary purpose of Colorado River water development, but instead has been a secondary use to serve other primary values. Dams have served as "cash registers" or, more accurately automated tellers, to pay for other water development that could not be financed by public or private capital in the region. For this reason, the law of the river neither mandates nor constrains modifications in the day-to-day operation of the river to accommodate new values. The law constrains the day-to-day operation on the river only in times of acute water shortage or water surplus. To understand the legal relationship between power generation and other uses, the role of hydroelectric power must be placed in the broader context of the changing values in the use of the Colorado River before we address the narrower question of whether dam operations may be modified.

HISTORY OF RIVER DEVELOPMENT

The history of Colorado River water policy has been determined by the politics of balancing conflicting beneficial use values. Geopolitics—balancing uneven rates of development among the upper and lower basin states—has been both a motivation and an enduring force in the development of the law of the river. Within the river basin states, economic development has been a sustained but not exclusive interest; social purposes such as building an irrigation society have also been important. The history of river use has been characterized by expanding multiple rather than single values. According to Wallace Stegner (1953, p. 353), "the whole Western future is tied to the multi-purpose irrigation-power-flood-control-stream-management projects . . . and the West's institutions and politics are implicit in the great river plans." As values changed or new values emerged, priorities in the management of the Colorado River have shifted to meet these changes.

The Colorado was dammed to reduce the risks of feast and famine, and minimization of risks, in particular the risks of long-or short-run shortages of water, remains a continuing preoccupation of the river's federal managers and the basin states. The arid West is not simply a scientific fact. Aridity has shaped the political culture of the basin states and the modern urban West. Fear of a long-term drought similar to the one that is thought to have driven the Anasazi out of the basin has historically animated western water law and politics and is the ethic of the water community. States have tried to accommodate unlimited growth on a limited water budget by providing ample margins of safety against shortages. As new uses have placed "calls" on the river, however, the law of the river has had to evolve to provide not only certainty but flexibility as well. While legal doctrines may have lagged behind changes in public attitudes, they have not prevented water policies changing to serve changing values that include equity to insular minorities and environmental quality.

The dreams of the first homesteaders, gold miners, and other settlers of the western United States to make the deserts bloom remain the compelling vision in the policies of water users today: an ample, secure water supply that will not run dry or be taken away. The fundamental doctrine of western water law—the rule of "first in time, first in right"—was conceived to allow investors to build projects that diverted water from mainstreams of rivers to lands sometimes remote from river basins (Tarlock, 1989, p. 331). The prior-appropriation doctrine also protected established beneficial uses of water by ensuring that later upstream diversions would not drain the water supply. Water law was fashioned not only to allocate water and to facilitate development but also to cushion development from risk of shortage and drought.

As agricultural and urban uses began to outstrip available water supplies, the western states persuaded the federal government to secure new supplies through carryover storage and interbasin diversion projects. The impetus for federal involvement went beyond economic development to include the social purpose of promoting Jeffersonian agrarian democracy in the West by supporting the settlement of yeomen farmers. In his December 1901 State of the Union address, President Theodore Roosevelt envisioned that "[t]he western half of the United States would sustain a population greater than that of our whole country today if the waters that now run to waste were saved and used for irrigation" (Martin, 1989, p. 30). This goal was never realized despite Congress's yeoman attempt to mandate yeomen.

The 160-acre-limitation provisions of the original reclamation act make clear the social purposes of Congress, which subordinate efficiency to distributional purposes. The Reclamation Act of 1902 provided interest-free federal loans and long payback periods for multipurpose projects whose principal aim was the agricultural settlement of the West. The federally developed water was used to attract small farmers to previously and and barren areas in order to create thriving communities. When farmers could not repay their debts, other legislation—beginning with a $20 million loan in 1910 and the Curtis Act of 1911 and continuing almost every year until the 1939 Reclamation Project Act—provided additional loans, extended repayment periods, or made it easier to renegotiate reclamation contracts. According to the *Congressional Record,* the 1914 Reclamation Extension Act was specifically intended to "create an irrigated empire in the West" (McCool, 1987, p. 68). Reclamation laws not only made available new water for irrigation but also reduced the risks involved to the developers.

DIVIDING THE WATERS: THE ORIGINS OF THE LAW OF THE RIVER

The certainty of water rights in the West has traditionally been left to state laws and interstate negotiations. Water allocation powers were ceded to the states immediately after the Civil War, and the federal government has never exercised its full constitutional powers over western water. While the federal government could provide money for construction, it could not provide the legal security necessary for development.

Of the seven states in the Colorado River basin, California developed most rapidly in both agricultural and urban areas. Southern California had long eyed the Colorado River as a potential source of water supply; however, early attempts to control the river's major floods were short term and for the most part unsuccessful. Additional attempts to persuade Congress to authorize construction of a multipurpose flood control, power, and storage dam in Boulder Canyon on the lower Colorado and the All-American Canal to deliver river water to southern California's Imperial Valley were also unsuccessful. Fearing that California and to a lesser extent Arizona would acquire eternal vested rights to Colorado River supplies under the law of prior appropriation, the then rural upper basin states used their representation in Congress to block all reclamation projects on the lower Colorado. Soon all states were forced to negotiate a compact.

The Colorado River Compact of 1922 modified the law of prior appropriation to allow development of the lower basin to go forward while at the same time protecting other geopolitical values. In exchange for upper basin support of Boulder Canyon project legislation, representatives of the seven basin states agreed to apportion the beneficial consumptive use of the Colorado's waters on the basis of territory rather than prior appropriation, thus reducing the risk of water shortage to the upper basin caused by California's expanding water demands. Lee's Ferry, Arizona at the mouth of Glen Canyon, was arbitrarily selected as the boundary between the basins, and the delegates attempted to settle the conflict over the development of the river by dividing the Colorado equitably between the upper and lower basins.

Structure of the Compact

Under Article II of the compact, the states of Colorado, New Mexico, Utah, and Wyoming became "States of the Upper Division," while Arizona, California and Nevada became "States of the Lower Division." In addition to providing equity between the upper and lower basins, the major purposes of the compact are:

> to establish the relative importance of different beneficial uses of water; to promote interstate comity; to remove causes of present and future controversies; and to secure the expeditious agricultural and industrial development of the Colorado River Basin, the storage of its waters, and the protection of life and property from floods (Article I).

The negotiators of the compact assumed that they were dividing an average annual flow at Lee's Ferry of 16 million acre-feet (maf). Article II(a) apportions "in perpetuity" the "exclusive beneficial consumptive use" of

7.5 maf annually to each basin, and Article III(b) grants the lower basin the additional right to the assumed 1.0 maf surplus. More specifically, because fluctuations or cycles of wet and dry years might diminish already established lower basin uses, Article III(d) provides that the upper basin states will not cause the flow at Lee's Ferry to be depleted by 75 maf for any consecutive 10-year period. In anticipation of the assertion of future claims by Mexico, the basin states provided that any amount granted to Mexico by treaty would be divided equally between the two basins.

The lower basin also retained the right to use any water not immediately put to use in the upper basin through a provision which declares that the upper basin states cannot withhold the delivery of water "which can not reasonably be applied to domestic and agricultural uses" [Article III(e)]. The lower basin's reciprocal duty not to demand the delivery of water for other than domestic and agricultural purposes is meaningless because the lower basin puts its entire river allocation to these uses. California was the major beneficiary of Article III, since its vested rights and existing uses were protected. In contrast, the upper basin states merely acquired the opportunity to use their entitlement as opposed to obtaining firm rights to the use of 7.5 maf per year.

Thus, the delegates gave highest priority to water use for agricultural and domestic purposes and to the protection of existing uses. Other beneficial uses such as power generation and navigation were also provided for in the compact, but at a lesser priority. For example, Article IV(b) expressly states that the impounding and use of water for hydropower "shall be subservient to the use and consumption of such water for agricultural and domestic purposes and shall not interfere with or prevent use for such dominant purposes," while Article IV (a) makes navigation "subservient" to the three other uses.

The Evolving Law of the River

Just as the Grand Canyon is a living geological record, the law of the river can be measured by time. Time helps define the law's different levels of commands. The law adopts different time horizons from the conceit of the eternal to the frantic pace of an hour. A time horizon also helps to chart the ever-increasing complex of accretions that are changing the law. For example, the law of the river speaks to the following time commands:

Eternity—The interbasin allocations and those allocations among the basin states.

Indeterminate—Possible flows necessary to protect endangered species.

Decade—The upper basin delivery obligations.

Year—Lake Powell fill obligations and the Lake Powell-Lake Mead balance.

Hour—WAPA's power generation decisions.

The classic law of the river is concerned with the eternal Old Testament commands, but the law is more complex than the original interregional allocations (Bloom, 1986, p. 139). For instance, the law of the river includes the totality of compacts, international agreements, treaties, judicial decisions, statutes that speak directly to the river and to water allocation generally, and the administrative practices that influence the allocation of the river. This expanded definition of the law encompasses both immutable commands and mutable principles.

DISTRIBUTING FEDERAL LARGESSE

The politics that combined agreement on the Colorado River Compact and Boulder Dam were the impetus for the creation of distributive federal water politics. Distributive politics contributed substantially to reducing the risk felt by the less developed states in face of California's successful bid for securing large quantities of real "wet" water. Legal allocations of water under the 1922 compact constituted only paper rights until they could be translated into congressional authorization and appropriations for projects. The informal rule of give and take developed in Congress dictated that the congressional delegations from each state would unite behind projects in their sister states. These policies led to construction of the large multipurpose reservoirs on the Colorado.

An understanding of the reasons that led to the construction of Boulder Dam and Glen Canyon Dam is essential to understand current conflicts, because the success of the basin states in securing single-purpose projects under the banner of multiple use opened the doors to the recognition of new interests and values. Boulder Dam was also important to the upper basin as well as the lower basin, not primarily because of the power it provided to operate and maintain the Boulder Canyon Project but because its hydropower revenues supported water development in the upper basin. Power revenues were eventually reinvested into the Colorado River Development Fund, a basin development fund authorized by Congress under the Boulder Canyon Adjustment Act of 1940 to be used for "studies and investigations by the Bureau of Reclamation for the formulation of a comprehensive plan for the utilization of the waters of the Colorado River system for irrigation, electrical power, and other purposes" (Goslin, 1978, p. 36). In addition, legislators from the rural, more slowly developing states were willing to support the dam on the promise that the support of the California congressional delegation would be forthcoming when a project benefiting their constituen cies was proposed. Congress came to authorize water projects in large-scale omnibus legislation with bundles of projects unrelated in hydrologic and economic terms tied together only by mutual political promises. Thus was born the iron triangle of the Bureau of Reclamation, Congress, and the basin states.

The linkage between power revenues and basin development runs throughout the history of river development. Under President Truman's Commissioner of Reclamation, Michael Straus, the Bureau of Reclamation began to advocate basinwide plans. This meant that power revenues could be used to finance small, inefficient irrigation projects. Navajo Dam in New Mexico is a classic example. Senator Clinton Anderson, the father of the 1956 Colorado River Storage Project Act, included this dam, which could not even pass muster under the Bureau of Reclamation's flawed benefit-cost procedures, in the act. As the senator's biographer has observed (Baker, 1985, p. 64):

> crucial to the future authorization of Navajo irrigation projects, the dam was merely New Mexico's entering wedge . . ., its guarantee that the state would have a project from revenues of larger power producing dams included in the Colorado River Storage Project.

The Colorado River Storage Project Act, which included Glen Canyon Dam, was the culmination of distributive politics which subordinated efficiency to regional development. The accumulation of hydrologic evidence and the drought period from 1931 to 1940 had upset the sense of security in the upper basin that it would be able to fully develop its legal water rights under the Colorado River Compact. Studies showed that the annual flow from 1906 to 1947 was only 14.2 maf per year, while in the decade of the 1930s only 10,151,000 acre-feet passed Lee's Ferry; the compact signed in 1922, however, had assumed a minimum of 16 maf as a basis for allocation. If the upper basin were to consume the 7.5 maf allocated by the compact, it would default on its obligation to the lower basin.

The engineering solution was to construct a dam in close proximity to Lee's Ferry that could store water in wet years and release water in years of shortages, thereby enabling the upper basin to meet its 1922 compact obligations while at the same time maximizing the upper basin states' future water uses. Thus, preservation of geopolitical equity was the major purpose served by Glen Canyon Dam. Power generation was clearly secondary to the need for revenues from ratepayers for future water development. According to Norris Hundley (1986, p. 30), Glen Canyon became the "cash register" generating most of the revenue through the sale of hydroelectric power to build a dozen so-called participating projects elsewhere in the Upper Basin." Further, Glen Canyon Reservoir was sized to leave room for the accumulation of silt predicted by conservationists to occur. However, in the end neither the law of the river nor federal carryover storage projects can provide enough security for the upper basin states. Denver's best water lawyers are trying to lay the foundations for reopening the 1922 compact through the contract doctrine of mutual mistake because of the original overestimate of the river's annual yield (Carlson and Boles, 1986).

Twelve years after Glen Canyon Dam was authorized, Arizona got its turn at the federal trough. The Colorado River Basin Project Act of 1968 was a water development spectacular, with multiple projects serving a variety of interests (Ingram, 1990). Tucked into the bulky package of legislation were projects serving each of the basin states that were neither hydrologically nor economically related but that brought political support. However, the reclamation era was ending. Among the items contained in the original legislation were two dams—in Bridge and Marble canyons, at either end of Grand Canyon National Park. The principal purpose of these structures was hydroelectric power generation to pump water from Parker Dam on the Colorado to the Arizona cities of Phoenix and Tucson through the huge and costly Central Arizona Project (CAP), which was the centerpiece of the legislation. Another purpose was to provide a cash register to pay for augmentation of the river to allow for future upper basin development. A study conducted by Tipton and Associates had convinced upper basin leaders, including Congressman Wayne Aspinall of Colorado, then Democratic chairperson of the House Committee on Interior and Insular Affairs, that there was insufficient long-term supply to serve lower river projects and allow for the upper basin to use its full entitlement. Aspinall was willing to support the CAP only if mechanisms were included, e.g., the dams to bankroll water transfer from a source such as the Columbia River (Ingram, 1990).

Hydropower at Bridge and Marble Canyon dams was viewed as an instrument and not as a major goal in itself in the Colorado River Basin Project proposal. The 1956 Colorado River Storage Project Act specifically stated that all projects, including Glen Canyon Dam, should be operated at their most productive rate to produce the greatest practical amount of firm capacity and energy. Certainly a high level of energy receipts was functional for maximizing revenues to the basin development fund for the repayment of reclamation loans and the construction of new projects. However, when maximizing energy conflicted with other values in the politics leading to authorization of the Colorado River Basin Project Act in 1968, energy production was clearly forced to take a secondary place.

The idea of flooding the Grand Canyon for profit became a lightning rod that attracted conservationist protest so strong that the entire package of projects was threatened by defeat in Congress (Ingram, 1990). In 1967, after complex behind-the-scenes negotiations, Secretary of Interior Stewart Udall announced that the administration was withdrawing its support for the dams in favor of a coal-fired generating station on Navajo Indian land. This action was taken without the support of Commissioner of Reclamation Floyd Dominy, who resented the Bureau of Reclamation becoming involved in energy production other than hydropower (Reisner, 1986, p. 300). Neither the amount of energy lost or gained nor the advantages of hydroelectricity to supply peaking power to serve growing cities was much of an issue. Instead, legislators were preoccupied with implications for the trust fund, with future water transfers from such distant areas as the Pacific Northwest, and with potential shortfalls of water supply. The delicate balancing involved in the politics of the Colorado River Basin Project Act was embodied in the multiple-use/multiple-value language adopted in the 1968 statute:

> This program is declared to be for the purposes, among others, of regulating the flow of the Colorado River; controlling floods; improving navigation; providing for the storage and delivery of the waters of the Colorado River for reclamation of lands, including supplemental water supplies, and for municipal, industrial and other beneficial purposes; improving water quality; providing for basic public outdoor recreation facilities; improving conditions for fish and wildlife, and the generation and sale of electrical power *as an incident of the foregoing purposes* [emphasis added].

This language, which specifies that the cash register benefits of energy production were to give way to other concerns if conflicts were to arise, takes precedence over the narrower directive made by Congress in the 1956 Colorado River Storage Project Act.

THE NECESSITY FOR FURTHER ALLOCATIONS: SECURITY UNDERMINED BY CONFLICT

The law of the river has never been static or free from risk, and the basin states live under an illusion of security. The 1922 compact was only the starting point for further allocations among the basin states. Further compacts, Supreme Court litigation, international agreements, and state and federal laws were necessary to firm up individual state rights and provide the large federal reservoirs necessary to guarantee delivery obligations. Additional interests that were initially omitted also had to be accommodated along with newly emerging values. The development of the law of the river has been extensively chronicled and analyzed. For our purposes, the important point is that most changes refine the regional mass allocations. The 1922 compact only divided the river between upper and lower basins; it made no attempt to allocate shares within each basin. By a compact signed in 1948, the upper basin states divided their 7.5-maf share among themselves by a percentage allocation. In contrast, the lower basin states fought over the division of their allocation in Congress, in the courts, and even on the Colorado's banks. The "fundamental error" of no intrabasin allocation was one of several reasons behind Arizona's refusal to ratify the 1922 compact until 1944, for while the compact protected the upper basin from California, it did not protect Arizona from California (Hundley, 1986, p. 19). In 1928 Congress approved the Boulder Canyon Bill, which authorized the construction of Boulder Dam and the All-American Canal on the condition that California agree to limit its legal rights to the Colorado's waters to 4.4 maf annually plus one-half of the surplus—a limitation California agreed to in 1929. In 1963 the Supreme Court held in *Arizona* v. *California* that when Congress enacted the Boulder Canyon Project Act it exercised its constitutional power to allocate interstate waters and thus implicitly apportioned the lower basin's share of the river. Consequently, California, Arizona, and Nevada received 4.4 maf, 2.8 maf, and 300,000 acre-feet of water, respectively.

Arizona v. *California* was the product of geopolitical forces. By blocking the federal construction of dams serving Arizona on the grounds that insufficient water existed in the basin, California failed to honor the rules of distributive politics. Arizona turned to the courts to adjudicate its water rights on the Colorado, and after 12 years Arizona's position was generally vindicated. In the course of its opinion, however, the Supreme Court elevated the status of other previously underappreciated values, and Arizona's great victory was pyrrhic. To secure federal financing of the CAP, Arizona had to agree to subordinate its decreed right to California's 4.4 maf entitlement [43 U.S.C. section 1521(b)].

ACCOMMODATION OF NEW VALUES

Even as multipurpose development was embraced as the way to pay for irrigation projects, new values previously slighted under the multipurpose balancing policies of the conservation era were emerging. For instance, at the same time that Congress authorized Glen Canyon Dam in the Colorado River Storage Project Act, another dam was defeated for environmental reasons. Echo Park Dam on the Green River threatened to back water into Dinosaur National Monument. The location of the dam in the monument was opposed because it might constitute a precedent for invasion of the national park system (Tarlock, 1987). Environmental quality was also at issue. The question was whether the natural beauty of the striated canyons in the Dinosaur National Monument were of sufficient value for the nation to forgo the economic, engineering, hydrological, and local political advantages of a dam at that location (Stratton and Sirotkin, 1959). Environmental values also increased in importance with the elimination of Bridge and Marble Canyon dams from the Colorado River Basin Bill of 1968. In 1977, Roderick Nash documented the change in prevailing values represented in the defeat of these two dams (Palmer, 1986, p. 86):

> [Boulder Dam's] completion in 1935 was a reason for universal jubilation in the United States. A wild river had been tamed. The engineers were heros, and as Lake Mead began to fill, a proud nation proclaimed Boulder Dam the eighth wonder of the civilized world. Thirty years later the tables were almost totally turned. Again engineers proposed a dam on the Colorado River—upstream from Hoover Dam in the Grand Canyon. But this time the engineers did not seem to be the agents of progress that they had been in the 1930s. For a great many Americans the Colorado River in the Grand Canyon was not a monster to be shackled and put to work for the economy but something valuable in its own right and already working to enhance the quality of American life. . . . In 1968 the cheers that forty years before greeted the authorization of Boulder Dam now sounded in support of the defeat of the Grand Canyon dam projects.

Thus, Echo Park touched off a decade-long debate about the merits of preserving wild and scenic rivers. In 1968 the big-dam era effectively ended with the passage of the Wild and Scenic Rivers Act.

Omitted Interests: Indians and Mexico

The development of the West was uneven in social as well as geographic terms. Much of this unevenness was due to inequities in access to the process of dividing up the river. According to Philip Fradkin (1984, p. 155), the Colorado was essentially a "white man's river" or more narrowly "an Anglo river" since:

> [e]ven within this last concentric racial circle, the river has been divided and diverted by only a very small segment of Caucasian society. Others do benefit, but only the few distribute the water. This small group of decision-makers and technicians has been invariably white, Anglo, male, and extremely conscious of how they wanted the economic benefits of water dispersed.

In 1922 the full range of relevant interests were not represented in the negotiations. The two most obvious exclusions were Native American Indian tribes and the government of Mexico. In the 1908 decision in *Winters v. United States,* the United States Supreme Court had given Indian tribes priority to large amounts of water—enough water for all of their future needs. The negotiators of the 1922 compact, however, refused to deal with Indian water rights. The compact left this issue to the courts and to Congress with the statement "Nothing in this compact shall be construed as affecting the obligations of the United States of America to Indian tribes" (Article VII). Native American rights continued to be ignored until the 1963 ruling in *Arizona* v. *California*. In its opinion, the Supreme Court took Article VII of the compact at face value by granting five Indian tribes located along the Colorado River a reserved right to the river's waters dating back to the establishment of the Indian reservations. Indian water rights were to be quantified by their "practically irrigable acreage." To satisfy these claims, the water is subtracted from the allocation of the state in which the reservations were located (Tarlock, 1987).

While not directly affected by hydroelectric power generation, the satisfaction of Indian water rights reminds us that there are a number of other values that must be served by contemporary water management. The rights of Indian people to the benefits of the Colorado River can no longer be ignored, and all decisions must be examined for their effects on Indian interests. Indian peoples have become increasingly aggressive not only in protecting their present water values but also in preventing water development that adversely affects relics of their heritage and religion. Archeological sites are protected by federal law and by strong political support. The net effect of these claims is to strengthen the political and legal case for the accommodation of omitted interests.

The rights of the government of Mexico to the Colorado's waters have also been accommodated by superimposing new rights onto the original mass allocation authorized by the Colorado River Compact. Mexico was granted a 1.5-maf annual share of the river in 1945 only after lengthy negotiations with the U.S. State Department (Meyers and Noble, 1967). This treaty was passed despite considerable opposition by California, which stood to lose the nearly 1 million acre-feet of surplus water that it was using at the time (Hundley, 1986, p. 27). Because the water flowing into Mexico was often too salty to be useful, in 1973 Mexico obtained additional water quality rights by a subsequent international agreement (Miller et al., 1986, p. 29).

Accommodating Emerging Values

In the past two decades, environmental values have evolved from marginal to paramount societal values. The Colorado River has contributed significantly to this evolution. The elimination of Echo Park Dam in the 1956 legislation and the two Grand Canyon dams in the 1968 statute is evidence that conservation groups could exercise veto power on water development that directly infringed upon core values of national parks and wilderness areas. In the environmental decade of the 1970s, environmental groups substantially extended their ability to insert themselves in water politics. As time progressed, other values joined in making claims against the developmental perspective that has long commanded major attention. Many of these new claimants are less well served by power generation than by economic development.

The accommodation of newer resource values such as use of the river for habitat maintenance, recreation, and the stabilization of riparian corridors such as the Grand Canyon has proved more difficult than blocking new dams. While these interests can be recognized through the creation of new water rights, protection of these interests requires management of existing dams on the river. The web of interconnected statutes, international agreements, and cases that make up the law of the river, however, is not designed to manage the river for the full range of resource values. Furthermore, all states have resisted management because of a fear that it will dilute their mass allocation consumptive use rights. This defect in the law of the river is becoming more acute as new values assert themselves.

The basis for the accommodation of new values was laid in 1963 in *Arizona* v. *California*. In addition to granting Native Americans the right to use as much water as they practically could to irrigate their lands, the Supreme Court granted reserved rights to federal land management agencies for federally reserved lands such as parks and forests. These non-Indian reserved water rights remain a source of great controversy. In the 1976 decision in *United States* v. *New Mexico,* the Supreme Court severely restricted the conditions under which these rights can be claimed when it held that public land management agencies can claim only federal reserved rights necessary to fulfill a primary water-related public land reservation. Still, because Grand Canyon National Park was set aside to preserve the Colorado River, this standard could be the basis for the Department of the Interior to argue that the enabling legislation allows the National Park Service to assert a federal reserved water right to protect the ecological integrity of the Grand Canyon.

Additional new values were incorporated in a number of national environmental statutes passed in the 1960s, although these new statutes were not integrated into the law of the river. The 1964 Fish and Wildlife Coordination Act, for instance, dictated that fish and wildlife were to be considered as primary values. The Fish and Wildlife Service, however, lacked sufficient power and resources in the early years to block project construction damaging to endangered species or habitat, and the act did not fulfill its potential on the Colorado. While it is too late to include such values appropriately in evaluating proposed construction of projects, such concerns can be included as criteria for water management.

Two notable statutes with considerably more potential to require river management are the Clean Water Act and the Endangered Species Act. These statutes superimpose environmental protection mandates onto existing water allocation regimes without specifying the extent to which prior allocations are modified, but the few court cases involving these statutes suggest that existing allocations are not a per se barrier to the accommodation of federal objectives. Together, the two acts strengthen the case for maintaining streamflow so as not to disturb delicate ecosystems and will play a much more important role in the future allocation of western waters than they have in the past.

The Wild and Scenic Rivers Act is further evidence of increased priority being placed on maintaining rivers in their natural state for preservation and human enjoyment. The National Park Service has struggled mightily with the issue of whether only oar-powered boats should be allowed in the Grand Canyon in order to protect the quality of the wilderness river experience. It is obvious that maintaining river levels in a stable condition also contributes to boater safety and enjoyment. Daily fluctuations of flows at peak power times are clearly not natural.

The 1972 amendments to the Federal Water Pollution Control Act established water quality and pollution control as significant federal values. The Colorado River Salinity Control Act of 1973 provided funding for new projects to reduce naturally occurring salinity such as in the Little Colorado tributary and mandated that other projects be managed to reduce the infusion of salt (Mann, 1975, p. 106). Some lower basin leaders have argued that the dangers and costs of increased salinity are sufficiently serious to forestall development in upper basin states. The adverse impacts of salinity will have to be taken into account in any future development and be considered in river management for hydropower as well.

HOW SHALL THE COMPUTERS BE PROGRAMMED: MANAGING THE RIVER IN THE SHADOW OF THE LAW

Although *Arizona* v. *California* established the Secretary of the Interior as the manager of the Colorado, the real managers are the Bureau of Reclamation and WAPA. The question is, Can these single mission agencies act as stewards for diverse interests? These agencies have historically been positioned to mediate among conflicting interests, and their jobs are becoming even more exacting as new claimants gather strength. For example, the "Mission of the Bureau of Reclamation" includes providing for:

> municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management and wind and solar power.

That the Department of the Interior officially recognizes the complexity of its role is evidenced by the content of the publicity it distributes:

> As the Nation's principle conservation agency, the Department of the Interior has responsibility for most of our naturally owned public land

> and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environment and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development *is in the best interest of all our people* [emphasis added].

Glen Canyon Dam is the linchpin of the management of the Colorado because it enables the upper basin states to store sufficient water to meet their 10-year delivery obligation to the lower basin states. Paradoxically, the law of the river controls the yearly operation of the dam but does not constrain daily operations for power generation. The reasons are that the law of the river affects power generation only in the case of long-term extreme shortage, while the law of reservoir operations is a law of annual fill targets.

The relationship between power generation and other uses of the river has been the subject of some speculation among commentators (Meyers, 1967; Getches and Meyers, 1986), but there has not yet been a conflict that tests the relationship. River experts have constructed a set of hypothetical scenarios, much like the Defense Department's doomsday scenarios, that examine the operation of the compacts under worst-case conditions. The issue has conventionally been discussed in the context of the upper basin's ten-year delivery obligation or its right to store water.

Because the delivery obligation is absolute, the upper basin states are precluded from objecting to the use of this water for power generation before it is consumed by the lower basin states. The issue then becomes a question of when the lower basin states can require upper basin water solely for power generation. For this scenario to occur in accordance with the requirements of the 1922 compact, there would have to be a prolonged drought that made it impossible for the upper basin to meet its 10-year delivery obligations and the lower basin states would have to demand the release of water for hydropower. The late Dean Charles J. Meyers suggested that if lower basin consumptive demands are met, Article III(e)—which expresses a clear preference for domestic and agricultural uses over power generation—prohibits the lower basin from demanding water solely for hydropower (Meyers, 1967, p. 20). Under this same logic, upper basin lawyers claim that when the upper basin is meeting its Article III(d) obligations, the states can hold water for carryover storage at the expense of power generation during times of surplus "to the extent needed to provide for their own allocated consumptive uses and to meet their obligations at Lee Ferry" (Clyde, 1986, p. 114). The subordination of power to irrigation and domestic use was continued in the Colorado River Storage Project Act, which directs the Secretary of Interior to produce the greatest practicable amount of power and energy that can be sold at firm power and energy rates consistent with the Colorado River Compact, the Upper Colorado River Basin Compact, the Boulder Canyon Project Act, and the Boulder Canyon Project Adjustment Act [43 U.S.C. section 620(m) and 42 U.S.C. section 1552(c)].

For the present, Glen Canyon operating criteria balance power generation with downstream consumptive demands but grant the Bureau of Reclamation and WAPA the discretion to manage the dam as a cash register or ATM. Daily dam operations take place in the shadow of the law of the river, but except during a multiyear drought cycle the shadow is a faint one. The Colorado River Basin Project Act directs the Secretary of Interior to develop coordinated operating criteria for Hoover and Glen Canyon dams to balance reservoir levels each year. These criteria are subject to three statutory priorities that protect downstream 1922 compact rights and maximize the amount of carryover storage to meet the upper basin's delivery obligations. The Bureau of Reclamation's current operating criteria attempt to maintain Lake Powell at 3,490-acre feet—the minimum level at which hydroelectric power can be generated—and to hold Glen Canyon Dam releases to 8.23 million acre feet annually, except when the active storage forecast for Lake Mead is lower or when increased releases can either serve domestic and agricultural beneficial uses or prevent Lake Powell spills. Monthly release targets try to achieve the annual operating criteria, but hourly schedules, although set to meet the monthly target, "are heavily influenced by the power demands and minimum flow requirements" (U.S. Department of the Interior, 1988, p. D-18). This allows higher releases in the peak winter and summer demand months.

CONCLUSION

The law of the river is not a barrier to changes in the operation of Glen Canyon Dam. As stated above, the many compacts, international agreements, treaties, judicial decisions, statutes, and administrative practices which together form the law of the river neither mandate nor constrain alterations in the day-to-day management of the river to accommodate new and emerging values. Current opposition to change has developed as a consequence of WAPA contract expectations supplemented by constituency perceptions that the dams will provide revenue for future basin development.

Modification of the operation of the dam, if mandated by Congress or as a result of the National Environmental Protection Act (NEPA) and GCES process, will not be easy because of these expectations. All users, however, share some risk of modification of their rights, and power contractee rights are no less vulnerable to reasonable modification than are other rights. Neither the Constitution nor the law of the river grants invariable rights to perpetual federal subsidies. Furthermore, if one is to believe the rhetoric of the Department of the Interior and the Bureau of Reclamation, developing the river in the interest of all the people is best served by providing for multipurpose values rather than single-purpose uses.

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2

The Role of Science in Natural Resource Management: The Case for the Colorado River

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INTRODUCTION

Our primary purpose here is to present information and then to foster reasoned discussion. The symposium is meant to be a review of extant information about the Grand Canyon reach of the Colorado River and a forum to discuss how better to apply science to the management of the Colorado River ecosystem in the Grand Canyon.

The great nineteenth century surveys of the American West, e.g., those of Lewis and Clark, Long, Pike, and Fremont before the Civil War and the King, Hayden, Powell, and Wheeler surveys afterwards, were dedicated to documenting the extent and location of natural resources for the people of the United States. These surveys were, in fact, an early application of scientific observation to document natural resources for purposes of planning for development.

Some of the information that John Wesley Powell developed is recorded in his 1878 report *Lands of the Arid Regions of the United States,* a trenchant bit of writing that presents a compellingly logical approach to the development of water resources for the "reclamation" of lands for agriculture (Powell, 1878). This document underpins a report of the National Academy of Sciences that led to the establishment of the U.S. Geological Survey by consolidating the Hayden, Powell, and Wheeler surveys in 1879 (Bartlett, 1962; Stegner, 1954). The report documented the extent of the western water resource for development, and it presented a logical rationale for federal government involvement. This eventually led to the establishment of the Reclamation Service as one of the U.S. Geological Survey's branches in 1902 (Watkins, 1983). Thus, development of the Southwest was hastened.

Powell's parallel ideas about (1) full surveys of irrigable land, (2) land grant size and water rights, (3) rules for making land grants to families, and (4) governmental boundaries (irrigation districts) being congruent with drainage basins are outlined in the early chapters of his report. It is ironic that the rapid pace of subsequent legislation and development outstripped any attempt to implement Powell's ideas. Such implementation might have precluded many of the conflicts that we are facing in this, the last decade of Reclamation's first century; at least the history of the West would have been quite different. It was the articulation of these ideas that brought Powell under his greatest pressure from development interests in Congress. His full logic did not prevail because it was too revolutionary. It contradicted a prevailing spirit of individual initiative and competition, the cooperative spirit of the Mormons in Utah notwithstanding (Stegner, 1954).

Powell's surveys, of course, are the ones that identify the beginning of the systematic accumulation of information that we will review in this meeting. This body of knowledge was gathered with careful observation, with quantitative measurement methods, and with insightful analysis. These processes were followed by common sense interpretation and synthesis. As such, the analysis was scientific. Powell followed those reports with aggressive and assertive translation of his ideas into federal public policy. Many said that he was acting in his own self-interest, to position himself to have national influence (Stegner, 1954). In any event, he was an extraordinary man.

I suggest that we dedicate what we do and say here to the early scientists and engineers who tackled difficult problems on the Colorado River with enthusiasm. By doing so, I ask that we keep in mind that more reasoned discussion would have served the common welfare in the 1890s. Surely, it should serve well 100 years later.

THE STRENGTH OF SCIENCE

If a logically compelling rationale for a long-term interaction between natural science and useful management of the river can be developed here, it will be based on candid understanding of the kinds of knowledge that science can and cannot yield. Science, as the general concept is used here, has several aspects. My use will entail a combination of these.

First, science is method. It is a way of knowing based on the premise that what our senses tell us is the truth. Observation with a keen eye, common sense, and careful recording are often all that is necessary to perform solid scientific inquiry. The modern trappings of science, electron microscopes, side-scan sonars, infrared radiometers, computers, etc., all marvelous inventions, are technological extensions of the keen eye that merely enhance powers of observation and analysis. Technological advances, however, do not replace common sense.

Observation and subsequent accumulation of facts lead directly to patterns of inductive reasoning, or empiricism. Knowledge emerges as a result of forming general concepts from the assembly of specific facts into coherent and consistent patterns. Understanding grows as concepts of how things work can be stated with increasing certainty. Such understanding can be checked by predicting the outcome of events correctly. Prediction, refined in terms of observational design and analytical procedure, is the basis for experimentation in science.

There is great danger, however, in concluding that the understanding has been "proven" by correctly predicting the outcome of events once, or twice, or thrice. Some uncertainty always remains; if the outcome were checked again, under different circumstances, events might not proceed the same way, or resulting observations would not be the same. Proof by means of correct predictions is tenuous at best.

On the other hand, if predictions are made in the form of cause-and-effect hypotheses and tests are performed by manipulating conditions and observing the subsequent events, always seeking evidence that would show the hypothesis to be untrue, the method becomes more powerful. This is the planned experiment. Of course, there are degrees of elegance and cleverness in experimental design, and there are various levels of analytical power to be applied to the results. The logic, however, is that if any results under experimental conditions show the hypothesis to be incorrect, the hypothesis can be rejected as false. Disproof, falsification, or rejection of incorrect hypotheses is more powerful because it is final. Experimental science develops knowledge most rapidly by rejecting what is not true, thus leaving the truth more and more certain with each experiment (Doyle, 1890; Popper, 1965).

Science also may proceed in the absence of empirical data. Deductive reasoning is theoretical; it depends on the thoughtful application of first principles. This aspect of science may lead to the development of abstract conceptual models, many of which may be represented in mathematical notation. These methods become most powerful when they result in predictive hypotheses that are followed by testing. Again, experimental design and analysis become central to learning new knowledge and developing information. In practice, both inductive and deductive (empirical and theoretical) approaches are used in combination, though not equally well by the same person. The crux of the matter, however, is that tentative ideas are put to the test by confronting them with facts.

Second, science is knowledge. It is the subset of all human knowledge that has accumulated according to the methods briefly outlined above. It represents our understanding of the universe in which we live and the objective understanding of our place in it. A feature of this body of knowledge is that it changes. What was thought to be true is routinely falsified. We are constantly reminded that our understanding is imperfect. This uncertainty about truth is a common condition among practitioners of science.

Science, among all human endeavors, is therefore relatively quick to find and correct its own errors. The drive to expose and learn the truth is tempered by the sure knowledge that truth is rarely certain, yet we are driven to find it because the excitement of discovering new knowledge is so rewarding. Errors in manuscripts are abhorred by authors, of course. Yet when they occur, they are found by peer reviewers, more often than not, before the articles are published. Errors that escape the review process and appear in the open literature are soon pointed out by "friends" and competitors. The risk of being humbled by errors forces conservatism on all but the most confident, audacious, or naive scientists. The value of review as an error screen and as a guard against fraud is a significant value that must attend the publication of scholarly scientific investigation.

Third, science is application. Distinctions between basic and applied science may be beyond the scope of what is necessary here, but methods are similar, rules of evidence are the same, and uncertainty remains. The polemic conflict between the two is not important.

Basic science is characterized as seeing the universe more as a puzzle to be assembled than as a problem to be solved. Progress is less definable; fads and hot topics are common as "corners" and "edge pieces" are established and as recognizable patterns take form.

Applied science is characterized by seeking solutions to particular problems; as such, applied science underpins technology. The full extension of applied science is thought by many to define engineering, where human utility is an important criterion. Much problem-oriented research is performed by engineering consulting firms, called in because it is inefficient for agencies to carry research staffs large enough to cover the potentially wide array of research needs.

An unfortunate feature of much applied research is that the emergence of problems often catches us unaware, with inadequate background information and with little time for the full development of scientific inquiry before management decisions must be made. This imposes a crisis atmosphere on many investigations. Under time-limited schedules investigations proceed, under pressure, until the time for decision arrives. Once the decision is made, the value of the results drops because there is no further need for the information by the decision maker. The researcher, meanwhile, must get on to the next contract, or "crisis." The results of such investigations are not often prepared for publication. Nevertheless, new knowledge is discovered routinely in the process, but it is rarely peer reviewed and it is barely accessible to others in agency reports, known as the "gray" literature.

Finally, science is public perception. It is a cultural concept with many shades of meaning. Science is what scientists do. Science is what the National Academy of Sciences or the National Science Foundation or the Bureau of Reclamation or the Geological Survey say it is. There is an authoritarian ring to this perception that is distasteful and incorrect. Being correct by rule of authority in science is nonsense.

This point is important to any consideration of applying science to management or public policy because the credibility of science risks being compromised or used inappropriately. Statements risk being misleading. Things are done in the name of science only because of the credibility that the term "science" carries with it. Most scientists are aware of this; most guard against it because credibility is a precious virtue. Some scientists, unfortunately, take inappropriate advantage of science's inherent credibility. Perhaps I dwell too much on this, but the subject of water management in the Southwest is potentially contentious. We must be cautious.

THE LIMITS OF SCIENCE

Despite its several strengths, there are limits to what can be known through the methods of science. Understanding and awareness of these limits, as the applications of science to management are discussed, should be useful.

Understanding and predictive success through scientific inquiry lead to the opportunity for using manipulation to control or to alter events in nature through management. This premise has been the very basis for the development of modern crop and livestock agriculture, of forestry management, and of the management of fisheries and wildlife, i.e., of the development of all renewable natural resources. Many management shortfalls or errors have been made because adequate scientific inquiry was left behind. Often a management practice is implemented to solve a problem with too little, or no, interest in checking to see whether the problem is solved. More damaging, the results of scientific analyses are suppressed because they run counter to short-term financial gain of natural resource exploiters.

Science is clearly a powerful way to learn about nature or to predict the outcome of events given a known set of circumstances, but science cannot make judgments about what outcomes are good or bad. These are value judgments that require other human systems for knowing. Science may serve in such decisions by (1) objectively documenting changes and rates of change, (2) making predictions about the potential outcomes of change, (3) helping to develop management options, (4) evaluating the feasibility of management goals, (5) making predictions about management utility and success, (6) assessing results, and thus (7) illuminating public choices, but science itself is valueless; i.e., it has no inherent mechanism to evaluate good or bad or to choose between right and wrong. Decisions about the desirability of management objectives are therefore beyond the purview of science.

MANAGEMENT CHOICES

So, choices of management goals in the Colorado River ecosystem become a central issue—the "tough nut." Several agencies and their constituencies are in conflict. How are these conflicts to be resolved? How perfectly can they be resolved? What is the range of management choices? How do we know when resolution has been reached, or management successful? Who gets to choose the management goals? If management goals are incompatible, who decides which goal takes priority? What are the costs? Who pays? These are some of the questions that the Bureau of Reclamation is being asked by other agencies and by the public as the future operation of Glen Canyon Dam is considered. All of them are beyond the purview of basic science.

Science can contribute significant information to people seeking answers, making decisions, and setting management goals. But the people must decide. They must decide how much information is needed before they choose.

Our goals for the symposium follow from two questions:

Question: What can science provide now?

Answer: The body of knowledge waiting to be applied to these particular problems will be reviewed by speakers in this symposium.

Question: What can science do on a continuing basis?

Answer: The application of science to management, in this case, may be novel. A rationale is offered below, will be discussed as the symposium proceeds, and can serve as a focal point as decisions about management goals are made, planned, and implemented.

THE CASE FOR THE COLORADO RIVER

There are adequate introductory descriptions of the Colorado River and its history published elsewhere. The three oversimplified points here are made only to underpin a rationale to wed science and management on a continuing basis. Background and more detailed discussion may be found in our report *River and Dam Management* (National Research Council, 1987).

First point: The construction of Glen Canyon Dam three decades ago imposed substantial changes on the Colorado River in Grand Canyon National

Park and elsewhere. The changes did not all happen at once. In fact, they continue to occur, they will continue for the foreseeable future, and they are related to the operation of the dam. The river is in disequilibrium. Our detailed knowledge of pre-dam patterns in natural processes is sketchy and, until this symposium, has been scattered. Nevertheless, the alteration of the river because of the dam is obvious.

Second point: The river in Glen Canyon and Grand Canyon changed in response to low flows while Lake Powell was filling (ca. two decades, 1963–1980). These flows were governed by releases called for in the law of the river and generation of hydropower as possible.

Third point: The river went through a period of high flow spills in 1983–1985, but it has been readjusting to controlled fluctuating flows during the postfilling decade (1981–1990).

The paces of many ecosystem changes vary in all of these periods, but they are thought to be long term relative to annual patterns (e.g., seasonal changes) and multiyear legal and economic patterns (e.g., law of the river and hydropower marketing cycles).

THE LONG-TERM INTERACTION BETWEEN SCIENCE AND MANAGEMENT

Some dispute that the operation of Glen Canyon Dam can (1) serve to control the release of water according to the terms of the Colorado River Compact, (2) generate hydroelectric power effectively, and (3) achieve management goals in the Glen Canyon and Grand Canyon reaches of the river. There will be, I suspect, considerable disagreement about the third of these suggestions. The issue has been raised, however, and so the following is offered as a preliminary approach to finding solutions.

ECOSYSTEM SCIENCE

Most ecosystem scientists believe that the talents and skills of several people from various disciplines are required to understand complex systems. The ecosystem approach begins with the understanding that the elements of the system and the processes that drive them are interconnected. Furthermore, no element of the system is independent of others. Thus, changing one component or process will change all others. The degrees of change and the rates at which changes happen vary, depending on degrees of connectedness and the effects of random events.

Phenomena in the Colorado River ecosystem offer examples. Sediment erosion, transport, and deposition are linked to hydrologic events, topogra phy, and geologic structure. These patterns were probably the most obviously changed by the construction of dams. Solution of materials (e.g., salts and nutrients) by the water from the drainage basin is dependent on solubility characteristics of the sources. They are further dependent on rainfall, whether it runs off or percolates into soils, the temperatures at which this happens, etc.

The subsequent fates of dissolved materials are mediated by chemical and biological processes that, in turn, are controlled by physical features such as sunlight, temperature, and hydraulic turbulence patterns. Many of these components, e.g., patterns of nitrogen and phosphorus distribution and rates of photosynthesis, both in Lake Powell and downstream, were changed by the dam. Some system components are less obvious, however, and change is proceeding more slowly.

The central point is that the changes are related to one another. This fact emphasizes that scientific inquiry must begin with definition of the components of the system and how they interact. When the elements of the system and their connections are defined, often resulting in a complex conceptual scheme, then and only then can the conceptual scheme be simplified or disaggregated into component parts for study.

To begin with investigation of component parts, or seek solutions to narrowly defined problems, leaves too much of subsequent synthesis and integration of useful information to chance. There is risk of missing important information by not considering how components are interconnected. Thus, some things may not be learned that are crucial to interpretation, or worse, corrective management actions may be taken that have unintended detrimental effects. Another risk is that insignificant or inappropriate components may be included in study plans, resulting in wasted time or misappropriated resources.

OPPORTUNITY FOR MANAGEMENT

The patterns and processes of the Colorado River ecosystem that are under consideration are changing slowly. Therefore, management protocols should seek to match the pace of phenomena. Subsequently, the pace of ecosystem responses to management will be similar so that the design of a performance monitoring plan should also match the pace of the change; i.e., our thinking and our actions should be long term.

Once a conceptual scheme of the interacting components is established and their relationships to changing flows are understood, then the chance to use the dam to achieve desired states can be considered. Knowledge can be used to predict and to control, that is, to manage.

However, management of a changing system can be expected to require continuous adjustment. A dam discharge regime that has desirable manage ment effects now may not have the desired effect a decade from now. Furthermore, unexpected responses to management discharges are likely because of uncertainty in understanding; any management plans to achieve particular goals will likewise be uncertain. The failure to achieve a management target will therefore require management corrections. This means that ecosystem responses to management should be checked with a sustained program of monitoring and research so that requirements for mid-course adjustments are known.

On the bright side, such corrections will be more certain to have desired results with each iteration because we will have learned about system responses to the previous management flows; i.e., some uncertainty will have been removed and new knowledge will result.

Thus, the sustained iteration of management and monitoring becomes a compelling way of documenting system status as it changes and of conducting useful scientific investigation. This is the simple rationale for long-term collaborative efforts between science and management among the sister agencies of the Department of the Interior. It is not a passive attempt to preserve an illusory or imagined pristine condition in the river but an active program to achieve predetermined desirable objectives.

New knowledge acquired in the process will serve management of rivers elsewhere in the world, a major societal benefit of such a program. As water resources approach their limits and thus require greater effort to maintain their quality, this new knowledge will have significant utility. This is an opportunity for claiming world leadership in an important aspect of natural resource management.

LONG-TERM MONITORING AND SUSTAINED EXPERIMENTAL RESEARCH IN MANAGEMENT TERMS

A long-term data base managed according to modern research data base protocols will document the changing status of the ecosystem. It also will help identify needs for management decisions and corrections. Analysis of the long-term record itself allows for the discrimination of long-term trends from cyclic phenomena (signals) and provides for analysis of short-term variation (noise) and the system's responses to management activities.

Analyses of long-term data sets can correlate system elements, but they cannot provide for understanding of cause and effect. They can, however, suggest the short-term experiments necessary to evaluate cause and effect, and they provide the information for planning such experiments. After experiments have been performed, the long-term record aids in their interpretation because the status of the system when the experiment was performed is known. Conversely, experiments aid the interpretation of the long-term record because cause and effect can be better understood.

This mutually beneficial interaction of long-term monitoring and short term research is powerfully compelling both with respect to monitoring the performance of management decisions by providing a way to adjust them and with respect to applying scientific methods to learn new knowledge about complex systems. A long-term program without experiment is weak because cause and effect cannot be known. Management protocols, which depend on knowing cause and effect, are therefore less certain to work.

On the other hand, a program of short-term experiments without the long-term record is weak because the results cannot be interpreted with as much certainty. Furthermore, the documentation of management responses is missing. This cannot be remedied because the long term record cannot be added later. The long-term monitoring should be renewed as soon as possible.

MANAGEMENT IN SCIENTIFIC TERMS

Natural ecosystem features (beaches, native fishes, riparian habitat) are likely management targets in the Grand Canyon National Park. Unfortunately, there are no preexisting river ecosystem models from which to borrow or from which to develop management protocols. On the positive side, there are some important long-term data sets from the Colorado River because of its historic importance. Furthermore, the very existence of Glen Canyon Dam provides a control structure just upstream from a national park of long standing, a protected reach of river with unusual potential opportunities for science and for management.

Thus, when dam operations for management purposes are thought of as manipulative experiments, long-term data collection becomes performance monitoring. The mixes between management and research, between basic and applied research, and between problem and puzzle become mutually supportive rather than divisive.

THE PRESENT STATE OF AFFAIRS

It is clear that long-term ecosystem management programs such as those being considered here will require commitment and detailed planning. Careful planning is essential because the approach is novel at this magnitude. It will take cooperation among the sister agencies of the Department of the Interior. It will take a pact of cooperation among scientists and managers. It will also take cooperation among scientists within government and those from the academic sector to the extent that needed skills do not exist in the agencies.

Approaching the task will call for commitment to institutional changes, for commitment to a program that will extend beyond the careers of indi viduals, and for willingness to think the unthinkable in terms of linking economics, policy, and law with science.

In theory this seems quite natural; in practice it seems intractable. Many factions are competing now. The assumption of effective leadership will be difficult because understanding and credibility are in short supply. The absence of credible information undermines the mutual trust that will be necessary to conduct scientific and unbiased evaluation of the effects of operating Glen Canyon Dam.

Recently, the Bureau of Reclamation, the Fish and Wildlife Service, the National Park Service and the Western Area Power Administration, all agencies with mission responsibilities (three in the Department of the Interior, one in The Department of Energy), have begun to prepare an environmental impact statement about the operations of the dam. These agencies have mission responsibilities defined by Congress. Thus, they view the river and the dam from such different perspectives, based on uses of the water resource in ways that are often incompatible, that the ecosystem perspective has been virtually impossible to develop. This difficulty was at the heart of the National Research Council criticism in December 1987, and it has not been corrected. To the extent that agency missions are incompatible and generate bias, they are more likely to be served than the truth about the effects of the operations of Glen Canyon on the basic geomorphic processes in the Colorado River as it flows from Glen Canyon Dam to Lake Mead. These are the processes that underpin river ecosystem function. Understanding them is centrally related to the level of uncertainty about management effectiveness.

The approach that works may take many forms and could engage different numbers of people, but the costs need not be high. The basic views that must be accepted are (1) that the phenomena being influenced by dam operations are occurring on time scales better measured in decades than in years and (2) that they are tied to hydrologic and geomorphic processes that have been changed and are changing. Therefore, if the changes are to be understood and managed, then the management, investigations, and monitoring must be scheduled to match the pace of events.

Candidly, I fear that this opportunity for designing a proper approach to conducting science in concert with management is slipping away. On the other hand, if the common welfare has not been served by the present way of doing things, then we should find another way. The simple facts of the matter remain (1) construction of Glen Canyon Dam caused dramatic changes in the Colorado River ecosystem, (2) operational options available at Glen Canyon Dam are greater than those required to meet the purposes for which the dam was built, and (3) the Grand Canyon National Park generates strong feelings among a significant fraction of the U.S. population. The opportunity is there if someone has the courage, the will, and the conviction to take advantage of it.

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3

Hydrology of Glen Canyon and the Grand Canyon

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INTRODUCTION-NATURAL FLOWS INTO LAKE POWELL

To understand the hydrology of the Colorado River in the Grand Canyon, we must know the natural flows that would have flowed through the canyon without the effects of manmade changes. We must know the effect of the manmade changes that result in the current inflows into Lake Powell. In addition, the law of the river affects the releases from Glen Canyon Dam. The law of the river includes the actual law, which determines the division of the waters between upper and lower states, and the interpretation of the law, which determines the interyear and interday variation of the releases to meet the law of the river. To understand the present concerns about the canyon reach of the Colorado, we must look at those natural flows, i.e., the flows during the filling of Lake Powell, and the sudden and abrupt realization that a full dam spills. The period from the closure of the dam until its spill is a transition period. The future hydrology of the canyon reach will be different from any hydrology yet experienced. This paper will not look at all facets of hydrology but rather will highlight what is needed in terms of data and analysis in order to better understand the hydrology of the Grand Canyon.

EARLY UNDERSTANDING OF COLORADO RIVER FLOWS

The Colorado River basin both above and below the Grand Canyon has been influenced by diversions from the early days of settlement of the West.

The Mormons settled along the Green River in Wyoming in 1854 and immediately began irrigated agriculture. Other irrigated settlements began in the 1870s along the lower Colorado in California, in the 1880s near Grand Junction, Colorado, in 1890 at Yuma and on the Salt River in Arizona.

The earliest assessment of the hydrology of the Colorado River basin and its potential for development was undertaken by E. C. La Rue, a hydrologist with the U.S. Geological Survey (USGS). N. C. Grover, then head of the Water Resources Division, wrote in the foreword to La Rue's second major work on the Colorado, "The need for further agricultural development in the Colorado River basin will increase gradually, while the demand for electric energy in the basin and in regions outside the basin, but within economic transmitting distance will increase more rapidly. It would not be economical, however, to proceed with a program of development that is greatly in advance of actual requirements. Such a program would be unwise because it's uneconomical and would surely result in losses of invested capital. It is important also that any developments . . . shall conform to a rational scheme for the full development of the river that will not needlessly sacrifice head available for power or unnecessarily waste water by evaporation from reservoir surfaces" (Grover, cited in La Rue, 1925, p. 5).

A considerable amount of data were available to La Rue for that first assessment of the hydrology of the Colorado. Stream-gaging stations were established by the USGS as early as 1895 on the Green River, 1902 at Yuma, and 1904 on the lower San Juan. The USGS established the gaging station at Lee's Ferry in the summer of 1921 and the station at Bright Angel in 1923. In 1925 Larue published Water Supply Paper (WSP) 556, which used records through the 1922 water year. He reconstituted streamflows from 1895 through 1922 for the Colorado River at Lee's Ferry by use of gaged records upstream and downstream. His estimate of the reconstituted mean annual flow equaled 16.8 million acre-feet, which was the same as that used for that period by Leopold (1959). "Under future conditions the flow in and below the Grand Canyon will be reduced. When development in the upper basin is completed . . . the average annual flow is estimated at 12,000 second-feet at Lee's Ferry" (La Rue, 1925, p. 9), which is about 8.7 million acre-feet per year. La Rue estimated the depletions from the river for irrigation for the period 1895–1922 and listed them in WSP 556.

Earlier, La Rue had written, "The Colorado-San Juan reservoir site is in Glen Canyon on Colorado River in northern Arizona and southern Utah. By constructing a dam at the head of Marble Canyon, a few miles below the mouth of the Paria River, to a height of 244 feet, a reservoir of 3,000,000 or 4,000,000 acre-feet would be formed . . . . The average annual run-off available for storage at the Colorado-San Juan reservoir site is about 15,000,000 acre-feet . . . . The position . . . is good . . . but the capacity of the reservoir might be seriously reduced in 50 years by the deposition of silt" (La Rue, 1916, p. 214–215). Thus, Glen Canyon and nearby sites were under consideration for development from the earliest assessments of the Colorado River basin.

THE EARLY HEARINGS ON DEVELOPMENT OF THE LOWER COLORADO

La Rue was the first USGS engineer assigned to the Division of Water Utilization for field work needed in the examination of withdrawals under the act of June 25, 1910, and in applications for rights-of-way for irrigation and hydropower projects across public lands, Carey Act segregations, and examination of land for designation under the Enlarged Homestead Act. La Rue emphasized that demands for water from the Colorado would exceed the available supply, and thus water losses by evaporation should be a serious and critical planning criterion.

La Rue advocated a principle of engineering determinism, which is the advocacy of a single best plan. He was hydrologically correct, but the principle of engineering determinism fails to consider uncertainty. Engineering determinism has controlled the development of the Colorado, as it has development of most water resources, and that may be a cause for part of the concerns with the Grand Canyon today.

Arthur Powell Davis, a nephew of John Wesley Powell, was head of the Reclamation Service, later the Bureau of Reclamation, from 1914 to 1923. Davis and the Reclamation Service wanted water and power for California and Los Angeles immediately. La Rue advocated phased, integrated development. In the planning of Boulder Canyon Dam and the division of the waters, Davis and the Reclamation Service prevailed.

UNCERTAINTY IN AVERAGE STREAMFLOW

The division of the waters was not finally settled, however, and the lawsuit *California* v. *Arizona* resulted. During that case, Luna Leopold and Walter Langbein of the USGS analyzed the water availability in the upper Colorado, the uncertainty concerning the availability, and the effect of evaporation on yield from the upper basin (Leopold, 1959). The message was that autocorrelation of streamflows (the tendency for high years to follow high years and for low years to follow low years) reduces the information concerning the mean flow of the river. An example of this is the fact that the last three years of runoff from the upper basin have been below normal. Also, northern California is in its fourth year of drought. Thus, more years are required to determine the water availability with a given level of reliability than would be the case if the water volumes that flowed in each year were completely random and unrelated. This is illustrated in Figures 3-1 and 3-2, taken from Leopold's paper. Figure 3-1 shows that the reduction of the variability in mean flow for records of streamflow in general is less than would be expected for a random sequence of uncorrelated flows. Because the reduction in variability of estimates of the mean flow is not as fast as for random sequences, a longer period of record is required to obtain a given level of accuracy concerning the mean flow. This amount of increased record is shown in Figure 3-2. Leopold's figure shows that 100 years of record is required to obtain as much accuracy as expected from an uncorrelated 25-year record. Leopold's analysis showed that the 70 years of record on the Colorado is the equivalent of a streamflow record with about 20 years of record of uncorrelated data.

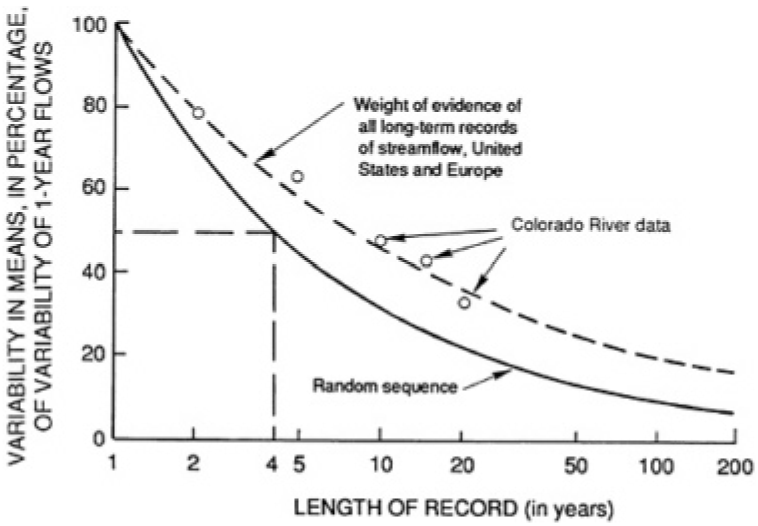

FIGURE 3-1
Variability of mean values of streamflow for records of various lengths.
SOURCE: Leopold, 1959.

Uncertainty in the average inflow results in uncertainty in the average yield, which determines the hydrology of the Grand Canyon. Uncertainty concerning hydrology determines the reliability of estimates of water and sediment throughput of the Colorado River and the resultant impact on growth and erosion of beaches in the Grand Canyon. The capability of Lake Powell and Lake Mead to store sufficient water to deliver the 75 million acre-feet every 10 years to the lower states plus 1.5 million acre-feet per year to Mexico depends on the reliability of the estimates of streamflow. The study of Leopold and Langbein should be updated, and the reliability of the "reconstructed flows" and the actual Lake Powell inflows should be reassessed.

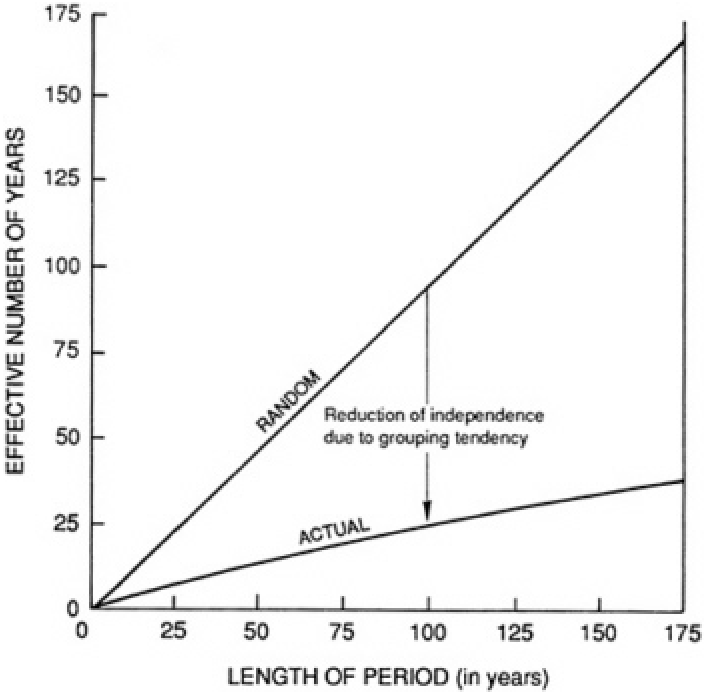

FIGURE 3-2
Effect of grouping tendency in streamflow.
SOURCE: Leopold, 1959.

EVAPORATION, BANK STORAGE, AND LAKE POWELL WATER BALANCE

Leopold also discussed increased evaporation resulting from added storage and the net effect on water availability. As we know, the effect of storage on streamflow is to reduce the variability and thus to increase the average yield from the basin. However, each additional increment of storage capacity gives a smaller increment of flow regulation and a smaller marginal increase in yield. Leopold demonstrated that an increase in total reservoir capacity in the Colorado River basin would achieve practically no additional water regulation if evaporation loss is subtracted from annual regulation. Evaporation loss offsets the hydrologic benefit of the regulation so achieved. Such an analysis should be updated routinely to determine the firm yield of the flows through the canyon and the capability of Lake Powell to deliver the contract amounts downstream as development increases upstream.

Evaporation loss from Lake Powell was assumed by La Rue to be about five acre-feet per acre per year, which amounts to about 750,000 acre-feet per year for the approximately 150,000 acres of surface area of the lake. Lake Mead evaporation was found to be about 7 feet per year (Harbeck et al, 1958). A similar evaporation at Glen Canyon would produce about 1 million acre-feet of evaporation per year. The U.S. Bureau of Reclamation (USBR) appears to use slightly under four feet per year (perhaps based on Jacoby et al., 1977), with a constant distribution in the year, irrespective of climate variation. USBR computes evaporation as a function of stage, however, so that their computed evaporation varies from 560,000 acre-feet for 1989 to 633,000 acre-feet for 1983 (USBR, 1965–1990). The U.S. Weather Bureau (USWB) (1959) estimates 80 inches per year for a Class A pan and a coefficient of .68 to convert to lake evaporation for an average loss of 4.5 feet, or about 15% higher than the USBR figure, which would give 650,000–730,000 acre-feet of loss per year. The USWB says 74% of the evaporation should be in May through October; USBR shows only 63%. Therefore, if lake evaporation is underestimated, it is in the spring runoff and summer months, when the reservoir will be highest in stage. An assessment should be undertaken to determine the basis for the seemingly low evaporation values used by the USBR, how they were determined, and how they are used. In particular, if they are used for the determination of releases, evaporation values should be based on local meteorologic data.

The USBR computes a water budget for Lake Powell on a daily basis. The water budget calculations are a basis for planning of releases from the dam. Therefore, an analysis should be undertaken to substantiate the USBR calculations. Evaporation is not a function of weather in the USBR estimates, as stated above, so when it rains and a cold front passes through, inflow rather than evaporation is affected. Therefore, inflow is a derived figure. Bank storage sometimes goes down when stage rises, and vice versa. For example, from September through December 1989, the stage is constantly falling yet there is a gain in bank storage each month. The stage falls over 11 feet, and bank storage increases by over 110,000 acre-feet. Therefore, bank storage must be a derived figure or at any rate seems not to be derived from a physically based model of the surrounding aquifer. The USBR should develop a physically based groundwater model for the determination of bank storage, such as is used in reservoirs in the Columbia River basin (Thompson, 1973, 1974). Such models are particularly useful if any long-term forecasts are used for managing releases from Lake Powell.

Many months have a water balance for Lake Powell for which inflow minus outflow equals the change in storage in the system, but some apparently do not. This may be because when results get too far from reality, adjustments are made to bring the apparent numbers back into agreement with the state of the system. Precipitation on the lake is not included in the water balance, as far as can be seen, although it should be included in any water balance calculations. Evaporation is computed as described above. Discharge is computed incorrectly based on turbine ratings. The discharge at the Lee's Ferry gaging station of the USGS should be used. If more accuracy is required, then a study should be undertaken to improve the accuracy at that station. If turbine ratings are used for day-to-day operations, then each turbine should be calibrated based on the USGS gage. The gravel bars immediately below Glen Canyon Dam should affect the different turbine ratings differently. A study should be undertaken to determine whether, in fact, some turbines are more efficient and what can be done to improve the performance of the less effective ones. Removal of part of the gravel deposits immediately below the dam might be feasible.

Change in storage in the lake is computed from a capacity table, which should change with sediment deposition in the upper reaches of the reservoir. A determination should be made of the effect of the changes in the storage on the capacity curve and thus on the water balance. There are two degrees of freedom in the USBR water balance for Lake Powell, apparently: bank storage and inflow. Because these calculations may influence what is released down the river, the calculations should be checked and verified. Bank storage should be calculated from a ground water model, such as is done in the Columbia River basin. Evaporation should be based on meteorologic data, such as suggested by the Lake Mead report. Precipitation should be taken into account; only then can a rational assessment of water availability be made.

RECONSTITUTED, NATURAL INFLOWS TO LAKE POWELL

Figure 3-3 shows the reconstituted natural inflows to Lake Powell. Shown are estimates by La Rue (1895–1922), discharges published by Leopold provided by USBR in 1959 (1896–1956), and current values used by the USBR (1906–1983). The data available at the time of the compact gave a mean discharge slightly greater than the 16 million acre-feet divided under the compact. The average after the compact is just over 14 million acre-feet, ending with and including the high water year of 1983. For the period 1923–1956, the current USBR estimates are about 500,000 acre-feet greater than the values provided Leopold (14.35 million versus 13.85 million). The figures provided by Leopold agree with the earlier figure of La Rue. The source of the difference of 500,000 acre-feet should be determined, and its validity should be assessed. Once again, releases may be determined by the accuracy of that determination. Certainly, long-term planning should be affected by the estimates of water availability. Subtracting 550,000 acre-feet of evaporation (possibly underestimated, as stated above) gives only 13.3–13.8 million acre-feet rather than the 16 million acre-feet needed to meet the contract. Who loses the evaporation is not known, but how this is decided will determine the total releases in the future.

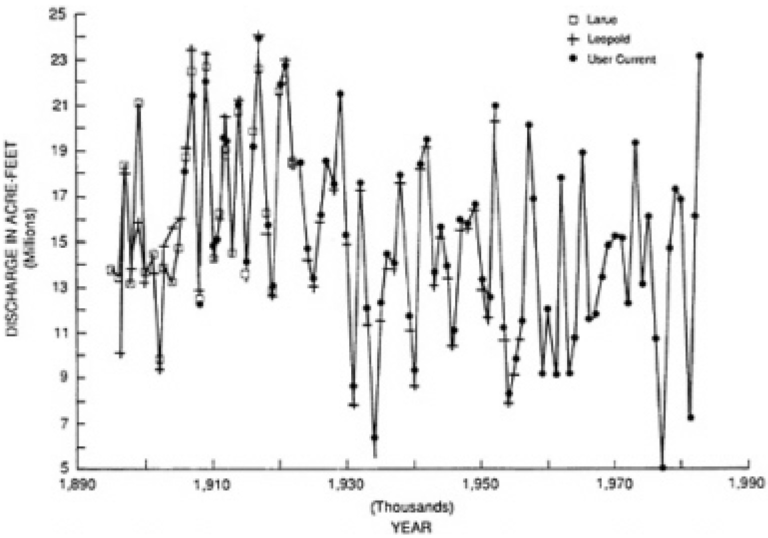

FIGURE 3-3
Reconstituted natural inflows into Lake Powell.
SOURCES: LaRue (1895–1922), Leopold (1896–1956), USBR (1906–1983).

GLEN CANYON AND THE RELEASE RULES

The release rules under the law of the river affect the flexibility of operation of Glen Canyon Dam and the flow of water through the canyon. Releases from Hoover Dam require releases from Lake Powell because the contents of Lake Powell are related to the contents of Hoover Dam. The "equal contents" rule keeps control of flows through the canyon in the lower states. Therefore, the release rules from Hoover Dam should be considered a part of the hydrology of the Grand Canyon.

The resulting hydrology of the Grand Canyon depends on water availability. That, in turn, depends on inflow into Glen Canyon, evaporation from the lake surface, storage in the lake and in its banks, precipitation on the lake, and water left for outflow from Glen Canyon. Hydrology controls the canyon.

RELATIONSHIP OF SEDIMENT TRANSPORT TO STREAM FLOW IN THE CANYON

Fluctuations of flow, not mean flow for the day, control sediment transport and stability of the ecosystem in the Grand Canyon. Pulses of flow released at Glen Canyon Dam will be attenuated as the flow travels downstream through the canyon. Daily flows alone cannot be used to predict sediment transport. Attenuation of flows will result in modification of the channel system, because the channel will adjust to carry the load of water and sediment imposed from upstream. Pools may fill in or bars (beaches) may be eroded or added to in the adjustment of the channel geometry to the hydrology. Because flow pulses attenuate as they travel through the canyon, the same daily average flow will cause the channels to adjust differently in different reaches of the canyon in order to carry the same sediment through the system. Added flows and sediment at the Paria and the Little Colorado determine the channel configuration, bars, beaches, and sediment discharge through the canyon. Therefore, discharge and sediment must be monitored for those two streams in order to understand the canyon flows and their relationship to the beaches.

Attempts to estimate sediment transport through use of a sediment rating curve require a considerable amount of data. The present set of data can be used to do a quick assessment of what flows are required to maintain an approximate balance of sediment throughout the system. This quick-and-dirty assessment will show what average set of high and low flows plus ramping rates will approximately move through the canyon the sediment available on an average basis. However, it will not predict where the sediment will be stored, and the channels will adjust during the period of transition to a quasi-equilibrium state. This results both from an inadequate data base (which must be improved by monitoring) and from an inadequate model with enough detail to predict changes in sediment transport for short reaches of the canyon. The sediment and discharge monitoring are necessary to verify the results of improved models of sediment discharge through the canyon. The canyon ecosystem cannot be managed properly without the data base and the analytical tools to predict flows and sediment discharges through the Grand Canyon.

Flows must cover the beach areas in order to add to them. Otherwise, all adjustment will be made by eroding beaches or adding bars which are wet at high flows. Therefore, this first assessment, which has not yet been made, is only a first step. The next step will require a model of beach building, based on the mechanics of flow in the vicinity of selected beaches, to determine what flows are required and how long to store sediments on the higher beaches and to clear the vegetation so that the beaches remain beaches rather than jungles of willows, salt cedar, and Russian olive. An understanding of the hydrology is necessary to predict and understand the movement of sediment in the canyon. An understanding of the sediment movement is necessary to predict the results of various flow regimes on the ecosystem of the canyon.

The rapids which make river running a challenge are the result of debris flows. If only average flows are maintained, the debris flows will collect at the rapids and not be reworked. Eventually, some rapids may become more dangerous if not impassable by boat. A study should be undertaken to determine what flows are necessary to move the materials that collect from debris flows in order to manage the rapids.

EFFECT OF OPERATION OF UPPER BASIN STATE RESERVOIRS ON GLEN CANYON AND THE GRAND CANYON

Present upstream use of waters in the Colorado River basin are on the order of a little over 4 million acre-feet, based on the difference between the USBR figures on water availability and inflows to Lake Powell. For 1968-1974 upstream depletions varied from 3.6 million acre-feet in 1969 to 4.96 million acre-feet in 1971, with an average of 4.28 million acre-feet for the 7 years. If 13.5 million acre-feet is available and 4.3 million is consumed upstream, this leaves 9.2 million acre-feet available to meet the downstream requirement of 8.25 million acre-feet (7.5 million acre-feet to the lower states plus half of the 1.5 million acre-feet to Mexico).

If water use increases by as much as I million acre-feet in the upper basin states, there is a possible effect on the future flow regimes through the canyon. Once the uses are in place, the depletions will increase so that the average inflow to Glen Canyon will be less than the required average release. This means that Lake Powell will be drawn down until an emergency results, at which time a lawsuit will start. A drought during the next 10 years after the start of the lawsuit and before its final adjudication can cause Lake Powell to go dry. At the very least, the lake level could change such that the temperature and chemistry of releases will change. During the next wet cycle Lake Powell may return to the "filling mode" similar to the period prior to 1983. As the upper basin states utilize their legal allotment and the average inflow approaches approximately the required average releases, major fluctuations in Lake Powell will result.

One effect of the fluctuation of the level of Lake Powell as average inflows decrease to be equal to or less than the average required release would be an increase in temperature in the release water. If Lake Powell goes dry or almost so, the releases will revert to warm water, and the area immediately downstream will become a warmwater fishery again. The trout population will be affected, if not eliminated. Management of the Glen Canyon National Recreation Area should be concerned with this problem and should be involved in any study of the future changes in average inflow into Lake Powell.

A general systems analysis of the inflows to Lake Powell and the effect of future increased usage by the upper basin states on those inflows should be undertaken. The uncertainty of water availability should be considered in the analysis, and the consequences of future development of increased water use by the upper basin states should be anticipated.

As mentioned earlier, autocorrelation in time of the streamflows in the Colorado River basin increases the uncertainty concerning the average streamflows in the basin. Autocorrelation in time means that high years tend to follow high years and low years tend to follow low years. Estimates such as 16 million, 14 million, and 13.5 million acre-feet of natural inflows to Lake Powell are very uncertain figures. Therefore, the possibility of wide variations in the elevation of Lake Powell is fairly large because that possibility depends on the assumed average natural inflow.

TRAVEL TIMES THROUGH THE GRAND CANYON

The storage behind Glen Canyon Dam attenuates the fluctuation in discharges while power production reintroduces them and controls the hydrology of released flows; then travel down the canyon attenuates the pulses. Rapid ramping rates cause the hydrology of the canyon to change as pulses are attenuated as flow travels downstream.

The travel time through the canyon varies with discharge. During 1987, the Grand Canyon Environmental Studies measured flows at four stations from Lee's Ferry to Lake Mead. By choosing selected peaks and troughs and tracing them through the canyon, peak and trough travel times as a function of discharge can be estimated. Figure 3-4 shows the variation of travel time from Lee's Ferry to the Little Colorado River and to Bright Angel Creek. The average velocities are from 6 to 8 cubic feet per second (cfs).

As stated, travel times through the canyon are a function of discharge. Peak flows travel faster than the lower flows in the daily trough (Figure 3-4). At a flow of 3,000–4,000 cfs, the travel time from Lee's Ferry to the Little Colorado is about 15 hours and to Bright Angel is about 20 hours. For flows of 18,000 to 20,000 cfs, these travel times are reduced to 12 and 15 hours. Because high flows overtake low flows and because the peakedness is reduced through dynamic storage, the duration of time for the trough discharge is reduced as the release wave from Lake Powell travels downstream. Because the sediment transport is related to a power of the veloc ity, as the pulse is attenuated less sediment will be transported, all other things being equal. However, all other things will not remain equal. The channel will adjust in those reaches where adjustment is possible and where the sediment transport is hydraulically controlled. Also, because the faster flows will overtake the slower, lower flows, the rising limb of the ramp will tend to steepen and the falling limb to be further attenuated by the effects of varying velocity.

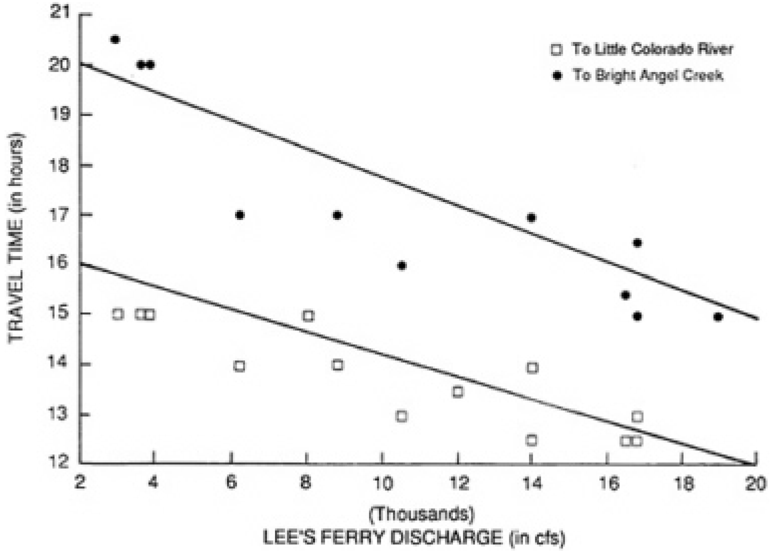

FIGURE 3-4
Relationship of travel time to stream discharge through the Grand Canyon from Lee's Ferry to Little Colorado River and Bright Angel Creek.

Thus, the difference in travel times will cause a steepening of the ramping rate on the rising stage and a flattening of the ramping rate on the falling stage, with that effect added onto the attenuation because of storage in the canyon reach. Thus, if the ramping rate is the same on the rising stage as on the falling stage, the changes downstream will be more abrupt on the rising stage.

To understand the change in flood waves and their effect as they move through the canyon, a firm data base is required. Because the velocity determines the sediment discharge, sediment monitoring is required as well as discharge monitoring. In fact, sediment monitoring is more important than water monitoring. A discharge routing model can be developed more easily and more accurately than can a sediment routing model. As stated earlier, sediment rating curves, the basis for most sediment routing models, will be difficult to define with sufficient accuracy to define a sediment routing model. This is because we are interested in differences in sediment movement over rather short reaches to determine the storage and erosion of beach materials. Therefore, an intensive monitoring network for sediment transport in the canyon will be needed to determine the sediment processes and how they interact. Bottom materials must be monitored to determine how the system is reacting during its transition to a quasi-equilibrium state. The bottom materials determine both the resistance to flow and the sediment transport.

The channel will adjust to the newly introduced regime of flows. Therefore, any analysis of travel times and sediment transport requires a longterm monitoring program. To understand the canyon, the changes in the canyon over time must be understood. The monitoring data are an integral part of any research plan, and they should be demanded by management in order to manage the canyon, to assess the effects of management decisions on the canyon, and to modify the decisions to adjust to the better understanding of the ecosystem that will result from the data obtained by the long-term monitoring.

CONCLUSION

The hydrology of the Grand Canyon depends on the water in Lake Powell available for release. The computation of natural inflow into Lake Powell, the projection of trends in the net inflow into Lake Powell, and the water budget for Lake Powell should be carefully reviewed and updated. Evaporation and bank storage in Lake Powell should be estimated through use of physically based models. Any tracing of flows through the canyon should be based on streamflow records at the Lee's Ferry gage, not on turbine computations of streamflow. Travel times for the various reaches of the Grand Canyon should be determined and used to calibrate flow and sediment routing models. Discharge and sediment must be monitored intensively in the canyon system. Monitoring of the streamflow and sediment should be considered part of the research effort, just as cataloging species of fauna and flora over time is a research effort.

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4

Sediment Transport in the Colorado River Basin

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ABSTRACT: The Colorado River basin in the southwestern United States is one of the most extensively regulated drainages in the world. Total storage provided by two large reservoirs, each with a usable capacity greater than 30 billion m3 and numerous smaller reservoirs, is approximately four times the mean annual runoff of approximately 17 billion m3/year. The relatively large reservoir storage capacity is required because of significant variations in annual runoff, a semiarid climate that necessitates irrigation to raise crops, and a need to meet the legal division of water among basin states.

Several of the longest daily sediment-transport records for North American rivers have been collected at gaging stations in the Colorado River basin. Many of these records of sediment transport are nearly 40 years in length. In 1990, daily samples of sediment transport were collected at only two gaging stations in the basin with more than 10 years of record. Water discharge has been recorded continuously at most of these gages for 60 or more years. Large reservoirs were constructed on each of the three major headwater tributaries during the early 1960s. Daily sediment transport and water discharge records collected at gaging stations in the Colorado River basin over the past 60 years demonstrate that an appreciable change in the hydrology of the Colorado plateau occurred about 1941, and they describe the pre- and postdevelopment hydrologic conditions. These data provide a unique opportunity to investigate the effects of climatic change and the operation of reservoirs on sedimentation and river channel stability.

Water and sediment are not contributed to the channel network uniformly across the Colorado River basin. Furthermore, the principal source areas of water and sediment differ greatly. A majority of the annual water discharge from the basin is supplied by the headwater areas. During the period 1941–57, eighty-five percent of the mean annual discharge is contributed by only 40% of the drainage area. Conversely, tributaries draining semiarid parts of the Colorado plateau, located in the center of the basin, supply 69% of the sediment load, although they constitute only 37% of the drainage area.

Because of the nonuniform supply of runoff and sediment within the Colorado River basin, the location of a reservoir profoundly affects its resulting downstream hydraulic impacts. The hydraulic and morphologic characteristics of river channels adjust over a period of years in order to achieve an equilibrium between the supply and transport of sediment with the available water discharge. Any substantial change in either the sediment load or the water discharge over a period of years will cause a corresponding adjustment in the river channel. The effect of a large reservoir upon the downstream river is complex because both the occurrence (duration) of particular discharges and the sediment load are altered.

INTRODUCTION

The Colorado River is one of the most highly regulated rivers in the world. Total usable reservoir storage capacity exceeds 70 billion m^3, or approximately four times the mean annual flow. The six largest reservoirs in the Colorado River basin, each with a usable storage capacity of I billion m^3 or more are shown in Figure 4-1 and listed in Table 4-1. The relatively large reservoir storage capacity is required due to significant variations in annual runoff, a semi-arid climate which necessitates irrigation to raise crops, and a need to meet the legal division of water among basin states. With the exception of relatively small tributaries, flow and sediment transport in the channels of the Colorado River basin have been extensively altered by the construction and operation of reservoirs. Therefore, it is important to understand how these reservoirs have changed the natural flow regime and the quasi-equilibrium adjustment of the channel characteristics to the quantity of sediment supplied to the channels.

The planning and design of the many reservoirs in the Colorado River basin required relatively precise knowledge of annual sediment load throughout the basin. Beginning in 1925, the suspended sediment concentration was sampled daily at two gaging stations in the Colorado River basin: the Colorado River near Grand Canyon, Arizona, and the Colorado River near Topock, Arizona. Over the subsequent 5 years, the sediment-sampling network was expanded to four additional gaging stations located on the

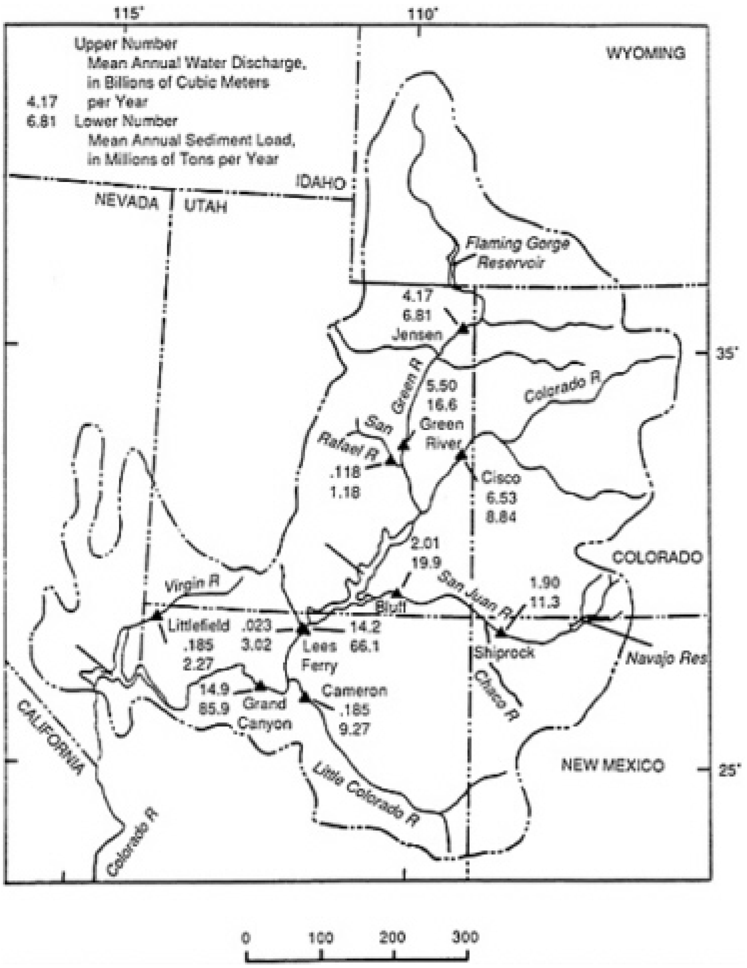

FIGURE 4-1
Mean annual runoff and sediment load at selected gaging stations in the Colorado River basin, 194–1957.

mainstem Colorado River and its major tributaries. By 1957, during the peak of reservoir construction, the suspended sediment concentration was being sampled daily at 18 gaging stations, each of which eventually had a record length exceeding 10 or more years. This network is the most extensive and detailed description of sediment transport in a large drainage basin ever collected. A majority of the reservoirs on the Colorado River and its tributaries were completed by 1963, and the perceived need for an extensive network of long-term sediment-sampling sites was greatly diminished. Sediment sampling was discontinued at one gaging station after another until by the mid-1980s sediment concentration was being sampled at only two of the gaging stations that had more than 10 years of record. Unfortunately, measurements of sediment transport at these gaging stations are not well correlated or indicative of conditions on the Colorado Plateau, which is the principal source area of sediment in the Colorado River Basin.

TABLE 4-1 Reservoirs in the Colorado River Basin upstream from Boulder Dam with more than 0.5 billion m3 of usable storage capacity.

Reservoir	Usable Storage Capacity (m^3)
Flaming Gorge Reservoir	4.3
Strawberry Reservoir	1.4
Blue Mesa	1.0
Navajo Reservoir	2.1
Lake Powell	31.0
Lake Mead	32.0
TOTAL	71.8

Over the past three decades, public recognition of the recreational, esthetic, and ecological values present in the streams of the Colorado River basin has grown immensely. Recreational boating through the canyons of the Colorado plateau is extremely popular. Most of these canyons are now included in national parks and national monuments. The Colorado River and its tributaries provide habitat for 11 endangered species of fish. Increased public awareness of the aquatic and riparian resources of the Colorado River basin has coincided with significant alteration on the river as a result of the regulation of flow by and deposition of sediment in reservoirs. Throughout the Colorado River basin, we must determine whether the basin's water resources are being managed wisely and in accordance with the numerous, sometimes conflicting, public benefits.

This chapter reviews our current understanding of sediment transport in the Colorado River basin. The primary objective is to identify and describe the spatial and temporal differences in sediment transport within the basin, which bears significantly upon the future management of the aquatic and riparian resource of the Colorado River basin.

HISTORICAL SAMPLING OF SEDIMENT CONCENTRATIONS

The first systemic samples of suspended sediment in the Colorado River were collected by C. B. Collingwood (1893) at Yuma, Arizona. Over a 7-month period from August 1892 to January 1893, a 1-pint sample was collected daily from the river surface. Samples were evaporated and the dry sediment combined into a monthly total from which an estimate of the sediment concentration was calculated. Beginning in 1900, suspended sediment samples were collected again in the vicinity of Yuma, Arizona, for various periods of time until 1909, when a continuous sampling effort was undertaken by the U.S. Bureau of Reclamation. The first samples of suspended sediment at gaging stations located within the Colorado River basin upstream from Yuma, Arizona, were collected by the U.S. Geological Survey beginning in 1904. Stabler (1911) summarized the measurements at 10 gaging stations in the Colorado River basin. Suspended-sediment concentrations were determined from surface samples collected at a single point in the river cross section during periods when the discharge was relatively constant daily.

These early efforts to describe the characteristics of suspended sediment transported in the Colorado River are difficult to evaluate. The concentration of suspended sediment varies substantially within a river cross section, being greatest near the stream bed below the high velocity and decreasing toward the water surface and the stream banks. Furthermore, the spatial variation in concentration increases with sediment particle size. Even at relatively large discharge when turbulent mixing is greatest, only the silt-and clay-size particles less than 0.062 mm in diameter will be distributed more or less uniformly within a river cross section. Thus, the suspended sediment concentrations reported by the studies cited above are surely less than the actual concentrations. Although the methods were rudimentary and relatively few samples were collected, some of the fundamental characteristics of sediment transport processes in the Colorado River basin were deduced by these early investigations. La Rue (1916) concluded that the largest monthly sediment loads were transported during the peak of the spring snowmelt which had large water discharge but moderate sediment concentration, whereas the largest concentrations of suspended sediment in the lower reach of the Colorado River typically occurred during September and October. La Rue also concluded that a portion of the basin, specifically southeastern Utah and northeastern Ari zona, contributed a disproportionately large share of Colorado River sediment.

Because of the need for more precise estimates of annual sediment load in planning reservoirs and the realization that sampling suspended sediment concentration at the river surface was inadequate, the U.S. Geological Survey developed a device and method for collecting a sample from the entire river cross section (Howard, 1930). The device was called the Colorado River sampler. It consisted of a 1-pint bottle held upright in a metal frame above a large sounding weight. The sampler was lowered to the riverbed, where a paper cap on the bottle was punctured by a messenger weight released from the surface; then the sampler was raised. Typically, several vertical segments of the river cross section were sampled and composited to determine the suspended sediment concentration at a given time. A program of sampling cross-sectionally averaged suspended sediment concentrations in the Colorado River at regular intervals began in August 1925 at the Grand Canyon and Topock gaging stations. Over the next five years, the sediment sampling network was expanded to four additional gaging stations: the Colorado River at Cisco, Utah, the Green River at Green River, Utah, the San Juan River at Bluff, Utah, and the Colorado River at Lee's Ferry, Arizona. The first 16 years of the Colorado River Sediment Project were described by Howard (1947).

In April 1944, a substantially improved suspended sediment sampler was adopted. The new sampler was designed so that water flowed into the collection bottle at the same velocity as the local streamflow without the presence of the sampler. During development, the new sampler was tested over a wide range of flow velocities and sediment concentrations and was found to collect a true discharge weighted sample of suspended sediment. With various modifications, this same sampler design is used worldwide today. A comprehensive study of the characteristics of the Colorado River sampler was never conducted. Various laboratory and field comparisons, including these conducted at the San Juan River at Bluff and the Colorado River near Grand Canyon, suggest that the Colorado River sampler would undersample the true concentration by a few to several percent.

The number of daily sediment sampling sites operated during each year from 1925 to 1990 in the Colorado River basin upstream from Lake Mead is shown in Figure 4-2. During the period from 1946 to 1956, the number of gaging stations where suspended sediment was sampled intensively expanded greatly. By 1957, suspended sediment concentration was determined daily at 18 gaging stations in the Colorado River basin where the record length eventually reached 10 years or more. The primary objective of this sampling network was to provide information for the planning and design of reservoirs in the Colorado River basin. Most of these reservoirs were completed by 1963, and the then recognized need for an extensive network of suspended sediment sampling stations was diminished. Gradually, one gaging station after another was eliminated. During the 1989 water year, suspended sediment was sampled daily at only two gaging stations in the upper Colorado River basin that had more than 10 years of record.

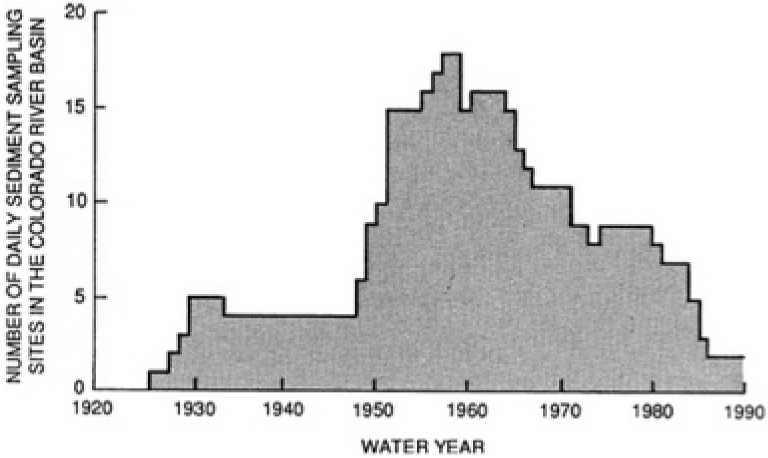

FIGURE 4-2
Number of active daily sediment sampling sites in the Colorado River basin with 10 or more years of record.

SOURCE AREAS OF RUNOFF AND SEDIMENT

Water and sediment are not contributed uniformly to the channel network of the Colorado River basin (Howard, 1947; Irons et al., 1965). Furthermore, the principal source areas of water and sediment differ greatly. Most of the annual water discharge comes from the headwater areas near the crest of the Rocky Mountains. Conversely, most of the sediment is contributed by the semiarid parts of the basin in southeastern Utah and adjacent States. The mean annual water discharge and sediment discharge measured during the period 1941–1957 at 11 gaging stations in the Colorado River basin upstream from Lake Mead are compared in Figure 4-1. After 1957, water and sediment discharges of the mainstem Colorado River and its principal tributaries were altered significantly as a result of construction of several reservoirs. The extent of water resource development prior to 1958, primarily irrigation and transmountain diversion, was modest, so that the values shown in Figure 4-2 are indicative of natural conditions.

Mean annual water discharge of the Colorado River near Grand Canyon from 1941 to 1957 was about 472 m^3/s, or 14.9 billion m^3/year, from a drainage area of 361,600 km^2. The combined mean annual discharge at the three farthest upstream gages shown in Figure 4-2 was 399 m^3/s, or 85% of the basin discharge at Grand Canyon. The contributing drainage area to the three upstream gages is 144,600 km^2, or 40% of the total drainage basin area. The estimated combined mean annual sediment discharge at these gaging stations was only 27 million tons/year or 31% of the total sediment discharge. Thus, the headwater tributaries contribute more than three fourths of the total water discharge but only about 31% of the sediment discharge of the Colorado River at Grand Canyon.

Most of the sediment discharged from the Colorado River basin is contributed by tributaries draining semiarid parts that include southeastern Utah, northeastern Arizona, and northwestern New Mexico. This area lies near the center of the Colorado Plateau. The largest of these tributaries, notably the San Rafael, Paria, Chaco, and Little Colorado rivers are shown in Figure 4-1. The portion of the Colorado River basin that lies upstream from Grand Canyon and downstream from Jensen, Utah, on the Green River, Cisco, Utah on the Colorado River, and Shiprock, New Mexico, on the San Juan River contributed about 59 million tons/year on an average, or about 69% of the basinwide sediment discharge, but supplied only 15% of the basinwide water discharge. The large sediment-contributing portion of the Colorado River basin upstream from Grand Canyon is 135,200 km^2, or ~37% of the total basin area. The most conspicuous sediment sources are areas of badland topography that developed on Mesozoic and Cenozoic mudstone and shale, principally the Wasatch, Mancos, Morrison, Chinle, and Moenkopi formations.

The characteristics of flow and sediment transport in those tributaries that supply most of the sediment to the Colorado River are not well known. Few gaging stations have been operated on these streams, and then only for a short time. The long-term contributions of water and sediment from many of these streams can be determined only by comparing the quantities measured at adjacent mainstem gaging stations. The only long records of water and sediment discharge for any of these tributaries have been collected on the Paria River to meet the requirements of the Colorado River Compact.

Mean monthly water and sediment discharges for the Colorado River before the construction of Glen Canyon Dam and discharges for the Paria River at Lee's Ferry are compared in Figure 4-3. Mean annual sediment discharge of the Paria River from 1947 to 1976 was 3.02 million tons/year or 4.6% of that transported by the Colorado River at Lee's Ferry. The mean annual water discharge, however, was only 0.72 m^3/s, or 0.16% that of the Colorado River at Lee's Ferry. Compared with the Colorado River basin, the Paria River basin yields three times as much sediment and one-tenth as much water per unit area.

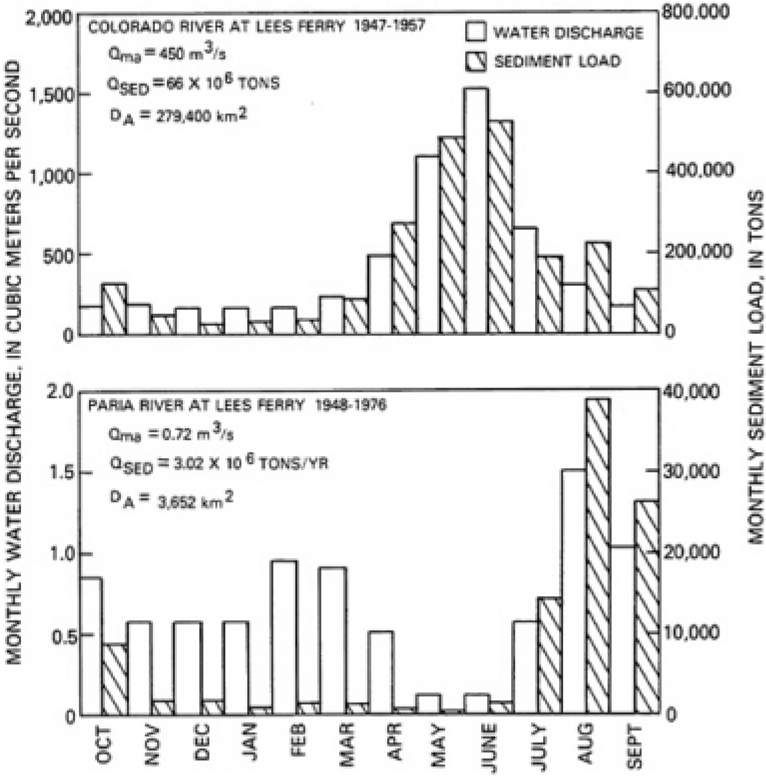

FIGURE 4-3
Mean monthly water and sediment discharges of the Colorado River and Paria River at Lee's Ferry, Arizona.

Maximum monthly water discharges occur in the Paria River during August and September (Figure 4-3). During the period of record from 1923 to 1986, two-thirds of the annual peak discharges occurred in the months of August, September, and October. These floods are a result of intense but short-duration thunderstorms that increase the discharge from a base flow of less than 1 m^3/s to several tens of cubic meters per second for a few days. The largest of these floods have transported most of the sediment outflow from the basin. Between 1947 and 1976, 50% of the sediment was transported on just 74 days, or just 0.7% of the time.

A comparison of the longest sediment records in the Colorado River basin upstream from Lake Mead indicates that the annual suspended sedi ment load for a given annual runoff was much greater before 1941 than after 1942. The relationship of annual runoff and suspended sediment loads recorded at the Colorado River near Grand Canyon between 1925 and 1957 is plotted in Figure 4-4. The mean annual suspended sediment load of the Colorado River near Grand Canyon was 195 million tons/year during the period 1925–1940 compared with 85.9 million tons/year during the period 1941–1957. A similarly dramatic decrease in the annual suspended sediment load for a given discharge occurred simultaneously at the Green River at Green River, Utah, Colorado River at Cisco. Utah, and the San Juan River near Bluff, Utah. Mean annual water discharges during the two periods 1925–1940 and 1941–1957 were approximately the same at all of these gaging stations. The large decrease in suspended sediment loads at about the same time that the new sampler was deployed is suspicious and disturbing. Smith et al. (1960) concluded, however, that the decrease was real. They based their findings on the following: (1) the shift to smaller suspended sediment load occurred from 1940 to 1942, whereas the new sampler was not in use until April 1944; (2) although the comparison of the two samplers was incomplete and the results were inconsistent, the difference between the samplers was not large enough to explain the decrease in annual sediment loads; and (3) the quantity of sediment deposited in Lake Mead during the period 1936–1948 was between 1,780 million and 1,840 million tons and agrees very well with the reported quantity of sediment transported past the Grand Canyon gage, 1,800 million tons.

The decrease in mean annual sediment loads in the Colorado River near Grand Canyon after 1941 is quite large, nearly 100 million tons/year, and raises some significant questions for those who are interested in the future of the Colorado River, in particular: What caused the annual sediment load to decrease so rapidly over a large area? What is the "normal" or long-term annual sediment load at a given site on the Colorado River? What was the source of the additional sediment, and will the sediment loads of the Colorado River increase to the pre-1941 level in the future? If so, when and under what conditions?

Beginning about 1880, channels of the Paria, Little Colorado, Chaco, and other tributaries of the Colorado were entrenched and large arroyos were formed (Cooke and Reeves, 1976; Graf, 1983). Vast quantities of alluvial sediment were eroded from the valley fills and transported to the Colorado River as arroyos enlarged. This widespread and dramatic geomorphic event has been studied for more than 90 years and continues to be a topic of interest. Webb (1985) compiled a list of 116 journal articles and books that described the chronology of arroyo development on the Colorado plateau and evaluated the importance of various causal agents.

Many investigators have concluded that large floods were the immediate cause of arroyos throughout the Colorado plateau (for examples, see Gre

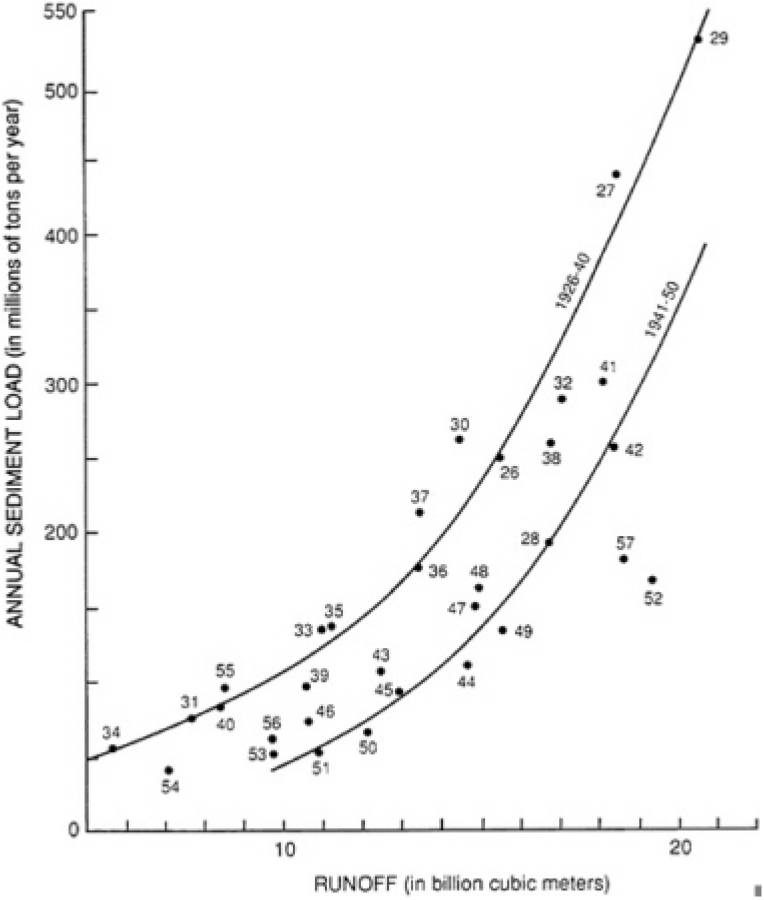

FIGURE 4-4

Relationship of annual runoff to annual sediment load in the Colorado River near Grand Canyon, 1926–1940 and 1941–1950. (Modified from an original by Smith et al., 1960.)

Source: Smith et al., 1960.

gory and Moore, 1931; Thornthwaite et al., 1942; Graf, 1983; Webb, 1985; and Hereford, 1984, 1986). In the case of Kanab Creek and the Fremont River, historical accounts identify the dates of floods that initiated and enlarged the arroyos (Graf, 1983). For most streams, the period of arroyo formation is known only to within a few years. Although arroyos developed in all major tributaries draining the and portion of the Colorado plateau during a 30-year span from 1880 to 1910, the period of intense arroyo formation varied from basin to basin. For example, entrenchment and arroyo development appear to have occurred somewhat later in the Escalante River, which drains the area immediately to the east of the Paria River. Using historical accounts and slackwater deposits, Webb (1985) determined that the Escalante River arroyo was initiated by a large summer flood that occurred on August 29, 1909. The arroyo was subsequently enlarged by recorded floods during 1910, 1911, 1914, 1916, and 1921.

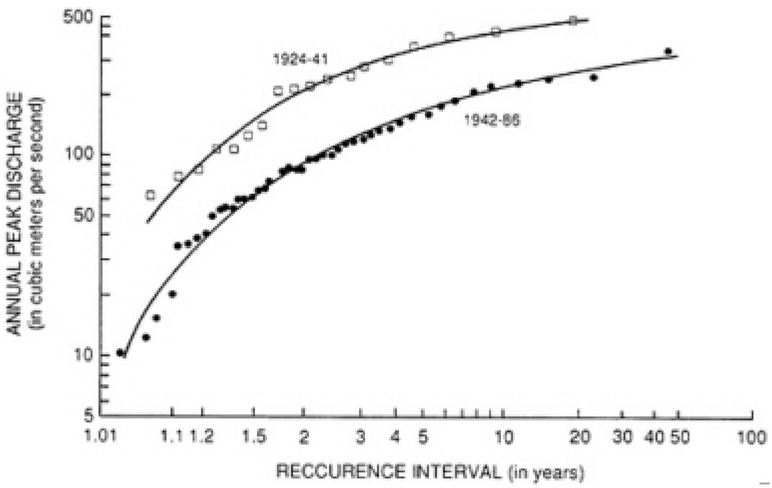

FIGURE 4-5
Comparison of recorded Paria River floods during the periods 1924–1941 and 1942–1986.

A change in the frequency of large floods is indicated by the time series of annual peak flows recorded at the Paria River at the Lee's Ferry gage shown in Figure 4-5. Large floods occurred more commonly before 1942 than since 1942. Seven of the eight largest floods of the Paria River since 1924 occurred before 1942. The mean annual flood of the Paria River since 1942 is 106 m^3/s, or 55% of mean annual flood, 220 m^3/s, recorded prior to

1942. Mean annual discharge of the Paria River at Lee's Ferry has decreased somewhat during the post-1942 period; however, the change is small compared with the decreased magnitude of annual peak flows. The mean annual discharge prior to 1942 was 1.03 m^3/s, compared with 0.77 m^3/s since 1942. The change is statistically significant at the 1% level. Hereford (1986) noted that the period of frequent larger floods corresponded to channel degradation and arroyo development. In contrast, the period of relatively small floods corresponded to channel aggradation and partial filling of arroyos.

Slackwater deposits along the Escalante River studied by Webb (1985) indicate that the frequency of Escalante River floods has varied during the past 2,000 years. Large floods occur most frequently between 1,200 and 900 years Before Present, 600 and 400 years Before Present, and in the past 100 years. The earlier periods of frequent floods appear to be correlative with previous Escalante River arroyos.

The sequence of channel changes in the Paria River basin as reconstructed by Hereford (1986), using stratigraphic, botanical, and photographic evidence, indicates that the channel degrades during periods of frequent large floods and aggrades during periods of small to moderate floods. An arroyo began to form in the Paria River channel in 1883 and attained its maximum size by 1890 (Gregory and Moore, 1931). The arroyo remained deep and wide until the early 1940s when channels throughout the basin began to aggrade. Within a decade of 1940, the Paria River channel narrowed appreciable and a vegetated floodplain developed. A comparison of the stage-discharge relationship determined at the Paria River at the Lee's Ferry gage before 1939 and after 1964 indicates that the channel had aggraded by as much as 2 m in storage. Since 1980, the Paria River channel has begun to degrade and widen (Hereford, 1986).

EFFECTS OF RESERVOIR STORAGE ON SEDIMENT BALANCE IN SELECTED REACHES OF THE COLORADO RIVER

As described above, the contribution of runoff and sediment per unit area varies greatly within the Colorado River. A majority of the annual runoff is contributed by the relatively high elevation (>3,000 m) parts of the basin along the Continental Divide, whereas most of the sediment is contributed by the semiarid parts of the basin near the center of the Colorado plateau. The downstream effects of a reservoir depend not only on the size and operating schedule of a reservoir but also on the location of the reservoir within the basin relative to the major runoff and sediment-contributing areas. An identical reservoir located at different sites in the Colorado River basin would have very different downstream effects on sediment transport and deposition.

GREEN RIVER DOWNSTREAM FROM FLAMING GORGE RESERVOIR

Andrews (1986) described the downstream effects of Flaming Gorge Reservoir on streamflow and sediment transport in the Green River. Prior to the construction of a dam in Flaming Gorge, a quasi-equilibrium condition appears to have existed downstream in the Green River channel; that is, over a period of years, the transport of sediment out of a given river reach equaled the supply of sediment into the reach. Since regulation by Flaming Gorge Reservoir began in 1962, the mean annual sediment discharge at downstream gages has decreased substantially. The mean annual sediment discharge has decreased by 54% (from 6.29 million to 2.92 million tons) at the Jensen gage, by 48% (from 11.6 million to 6.02 million tons) at the Ouray gage, and by 48% (from 15.5 million to 8.03 million tons) at the Green River, Utah, gage. The decrease in mean annual sediment discharge at the Ouray and Green River, Utah, gages far exceeds the quantity of sediment trapped in the reservoir.

Post-reservoir annual sediment budgets show that a majority of the Green River channel is no longer in quasi equilibrium. Three distinct longitudinal zones involving channel degradation, quasi equilibrium, and aggradation were identified. Beginning immediately downstream from the dam and extending downstream 110 river km, sediment transport out of the reach exceeds the tributary contribution, and the channel is degrading. The length of the degrading reach, however, is relatively limited because of the large quantity of sediment supplied by tributaries.

In the reach between river km 110 and 269 downstream from Flaming Gorge Reservoir, the quantity of sediment supplied to the reach from upstream plus tributaries approximately equals the transport of sediment out of the reach over a period of years. This reach appears to be in quasi equilibrium, as there is no net accumulation or depletion of bed material. Downstream from river km 269 to the mouth (river km 667), the supply of sediment from upstream and tributary inflow exceeds the transport of sediment out of the reach by 4.9 million tons/year on an average.

The decrease in mean annual sediment transport at the Jensen and Green River, Utah, gages since 1962 is due entirely to a decrease in the magnitude of river flows that are equaled or exceeded <30% of the time. The quantity of sediment in transport at a given discharge downstream from Jensen, Utah has not decreased in the post-reservoir period. Daily mean water discharges with a duration of 5% or less have decreased in magnitude by 25% during the post-reservoir period at both the Jensen and Green River, Utah, gages. The magnitude of daily mean discharges with a duration >30%, however, has increased to the extent that the mean annual runoff measured during the pre- and post-reservoir periods is virtually unchanged at both gages. The decrease in annual sediment transport thus results from a more uniform annual hydrograph rather than from a decrease in the annual runoff.

Ferrari (1988) described a detailed survey of sediment deposition in Lake Powell for the period March 1963 to September 1986 and concluded that 1.07 billion m^3 of sediment had been deposited in the reservoir. Assuming a unit mass of 1.04 tons/m^3 as determined by Smith et al. (1960) for Lake Mead, 1.11 billion tons of sediment accumulated in Lake Powell over the 24-year period. As described above, the mean annual sediment load of the Colorado River at Lee's Ferry during the period 1941–1957 was 66.1 million tons/year. This gaging station is located only 23 km downstream from Glen Canyon Dam, and there are no significant tributaries to the intervening reach. Thus, the quantity of 66 million tons/year is probably a reasonable estimate of the amount of material that would have been deposited in Lake Powell from 1963 to 1986 if there had been no additional development of water resources in the upper Colorado River basin after 1957. The actual mean annual accumulation of sediment in Lake Powell is about 44.4 million tons/year or 19.7 million tons/year less than the 1941–1957 average. The mean annual quantity of sediment deposited in major reservoirs upstream from Lake Powell is approximately 4 million tons/year. The remaining quantity of sediment, approximately 15.7 million tons/year, is sediment supplied to the principal upper basin tributaries, the Green, San Juan, and mainstem Colorado, but is not being transported downstream because regulation has greatly diminished peak discharges.

COLORADO RIVER DOWNSTREAM FROM GLEN CANYON DAM

Presently, the effect of various discharges in the Colorado River downstream from Glen Canyon Dam upon the riverine environment of Grand Canyon National Park is being studied in great detail. The contribution of sediment to the Colorado River through Grand Canyon is especially important, as it will influence significantly the distribution and size of sandbars (commonly called beaches) along the Colorado River. These sandbars are deposited during periods of relatively large discharge and become exposed when the stage falls. The bars are composed of sand with a median diameter of about 0.20 mm, with less than a few percent coarser than 0.50 mm, Schimdt and Graf (1990). Sediment particles of this size are transported primarily suspended within the main core of flow at commonly occurring flows. These particles, however, settle out and accumulate in areas of relatively low turbulence along the channel margin.

The National Park Service is concerned with the decreases in size and number of sandbars since the closure of Glen Canyon Dam in 1962. They have identified the preservation of sandbars as one of their highest-priority objectives. Sandbars are used by river runners as camp sites. They are also important features of the riparian and aquatic ecosystem. Fundamentally, the maintenance of sandbars along the channel margin of the Colorado River through Grand Canyon depends on determining the discharge and its duration which will build sandbars without causing a net depletion of the sand-size material in the Grand Canyon reach. Our understanding of current sediment inflow and outflow from the Grand Canyon will be described below.

The downstream effects of Glen Canyon Dam on the Colorado River differ somewhat from those of Flaming Gorge Dam. Glen Canyon Dam is located downstream from significant sediment-contributing areas, and therefore a relatively large quantity of sediment is deposited in Lake Powell. The quantity of sand-size sediment stored in the channel bed, banks, and floodplain of the Green River downstream from Flaming Gorge Reservoir is very much greater than the quantity of sand-size sediment stored in the Grand Canyon in both absolute and relative terms compared with the historical mean annual loads. The relative large discharges that have historically transported most of the sediment through Grand Canyon, however, have also been greatly reduced. The Paria and Little Colorado rivers join the Colorado River downstream from Glen Canyon Dam and contribute a large quantity of sediment (Figure 4-1). During the post-1941 period, these two tributaries supplied approximately 12.3 million tons of sediment per year to the Colorado River.

A comparison of mean annual sediment load during the period 1941–1957 indicates that the sediment load at the Colorado River near the Grand Canyon exceeded the sediment load at the Colorado River at the Lee's Ferry by about 20 million tons/year, see Figure 4-1. The difference between the quantity of sediment supplied by the Paria and Little Colorado Rivers, which represent 93% of the intervening drainage area, and the increase between the Lee's Ferry and Grand Canyon gages can be explained by (1) a few percent error in either the Grand Canyon or Lee's Ferry sediment sampling records and (2) net erosion of the reach between Lee's Ferry and Grand Canyon that occurred during the period 1941–1957.

It is reasonable to expect that the quantity of sand stored within and adjacent to the channel of the Colorado River through Grand Canyon increased between 1880 and 1941, during the period of relatively large sediment load, and that the quantity of sand stored in the channel has decreased since 1941. At present, there is no direct evidence for or against this hypothesis except the analysis of D. Burkham (personal communication) showing a 1.6-m decrease in the low-flow streambed elevation at the Lee's Ferry gage from 1941 to 1957.

The mean annual sediment load of the Colorado River near Grand Canyon under the present conditions cannot be stated with great certainty because daily sampling of sediment concentration at this gage was discontin ued in 1972. An estimate of the mean annual sediment load may be computed from the recorded daily discharges, and a relationship may be derived from the correlation of occasional samples of sediment concentration and the instantaneous discharge. Using this approach, the estimated mean annual sediment load of the Colorado River near Grand Canyon is approximately 11 million tons/year under present conditions, compared with 85 million tons/year during the period 1941–1957, immediately prior to the construction of Glen Canyon Dam. In contrast to the situation on the Green River downstream from Flaming Gorge Reservoir described above, the decrease in mean annual sediment load in the Colorado River near Grand Canyon is not solely due to a decrease in relatively large discharges. The concentration of sediment suspended in the flow at the Grand Canyon gage for a given discharge has decreased by a factor of 2-3. This decrease is undoubtedly due to a net depletion of sand-size sediment stored within the active channel, `1,400 m^3/s, since the closure of Glen Canyon Dam in 1962.

A comparison of sediment supply from tributaries and the transport of sediment downstream indicates that the Colorado River through Grand Canyon is approximately in equilibrium under the current operating schedule at Glen Canyon Dam. That is, the inflow of sediment appears to approximately equal the outflow of sediment over a period of years. The quantity of sediment stored in the reach between the Lee's Ferry and Grand Canyon gaging stations is estimated to be approximately 40 million tons (T. J. Randle and E. L. Pemberton, written communication), or less than four times the mean annual flux of sediment. Thus, even a relatively small, but persistent imbalance between the inflow and outflow of sediment to this reach over a period of years will cause appreciable changes in the quantity of sediment stored within the reach.

A long-term equilibrium between sediment inflow and outflow from the Grand Canyon reach, however, will not be sufficient to ensure the presence of large, exposed sandbars along the channel margin at commonly occurring flows. These bars are built and maintained by sustained periods of flow sufficient to inundate the bar crest by a few feet. Without sustained periods of high flow, the existing sand bar will be degraded through erosion of material and the encroachment of vegetation.

Periods of sustained, high flow followed by a corresponding decrease in flow throughout the remainder of the year will increase the mean annual sediment load of the Colorado River through Grand Canyon. The comparison of sediment inflow and outflow from the Grand Canyon reach described above suggests that the downstream transport is currently about equal to the tributary contribution. The challenge is to select the range of flows that will maximize the accumulation of sand on bars without exceeding the long-term rate of sediment supply. Our ability to define the optimum range of Colorado River flow through Grand Canyon depends on knowing in great detail (1) the long-term rate of sediment supply by tributaries to the mainstem Colorado River, (2) the longitudinal variation in the quantity of sediment transported at a given discharge, and (3) the dynamics of flow and sediment transported in areas of lateral flow separation (eddies), which control the deposition and erosion of sand bar deposits. At this time, we do not understand any of these topics well enough to determine precisely the range of streamflow that will maintain and, we hope, enhance occurrence of sandbars through the Grand Canyon reach.

CONCLUSION

Long-term daily sampling of suspended sediment transport began in the Colorado River basin at the Grand Canyon gage in 1925. Over the next three decades, the network of sediment sampling sites was expanded greatly. In 1957, there were 18 gaging stations where suspended sediment concentration had been sampled daily for 10 or more years. The network of sediment sampling sites in the Colorado River is probably the most extensive and detailed ever operated.

The primary objective of this sediment sampling network was to provide information for the planning and design of reservoirs in the Colorado River basin. Most of these reservoirs were completed during the early 1960s, and nearly all of the sediment sampling sites have been discontinued. During the 1989 water year, sediment concentration was sampled daily at only two gaging stations in the upper Colorado River basin. In recent years, public interest in and concern for the aquatic and riparian resources of the Colorado River basin have increased greatly. Comprehensive management of these resources will require rather detailed knowledge of sediment supply, transport, and deposition. Extensive analysis of the available sediment transport information using sophisticated water and sediment routing models together with reestablishment of selected long-term sediment sampling sites in the Colorado River basin will be necessary to achieve this goal.

Water and sediment are not contributed uniformly to the channel network of the Colorado River basin. Furthermore, the principal source areas of water and sediment differ greatly. Most of the annual water discharge comes from the headwater areas near the crest of the Rocky Mountains. Conversely, most of the sediment is contributed by the semiarid parts of the basin near the center of the Colorado plateau. There is also an important difference in the season of flooding between the principal source areas of water and sediment. In the high-elevation parts of the basin, major tributaries, and the mainstem Colorado, the flood season occurs in the spring, associated with snowmelt. Conversely, the tributaries draining the high-sediment-contributing parts of the basin flood most often during late sum mer and early fall as a result of thunderstorms. Throughout the Colorado River basin, floods transport a majority of the annual sediment load. Thus, a majority of the sediment load of the Colorado River is contributed to the channel by tributaries during July, August, and September; however, it is transported in the mainstem during April through June. The largest concentrations of suspended sediment in the Colorado River and its major tributaries occur during the season of maximum sediment supply rather than maximum sediment transport.

The respective flood seasons of the principal water and sediment source area are associated with different atmosphere circulation patterns. Furthermore, long-term changes and shifts in the relative strength of either pattern appear to be largely independent of the other pattern. Therefore, periods of relatively large sediment supply to the Colorado River and its major tributaries do not necessarily correspond to periods of relatively large flood flows in the Colorado River and its major tributaries.

During the period from 1880 to 1941, floods were larger and more frequent than in the period since 1941. Vast quantities of sediment were eroded by those floods, and large arroyos were formed in all of the tributaries draining the Colorado plateau. Suspended sediment concentrations at a given discharge as well as the annual sediment loads of the Colorado River and its major tributaries were substantially larger before than after 1941. The relatively large suspended sediment concentrations were probably associated with an increase in the quantity of sand-size material stored within the channel. Enlargement of these arroyos has been reversed since 1941, and significant quantities of material have been deposited in the arroyo channels over the past 50 years. The water and sediment discharges of tributaries to the Colorado River draining the Colorado plateau region have been sensitive to changes in climate over the past century. Further study of the relationship between the hydrology of these streams and variations in the regional climate should be undertaken.

The Colorado River is one of the most highly regulated rivers in the world. Total reservoir storage capacity is approximately four times the mean annual runoff. With the exception of relatively small tributaries, flow and sediment transport in the channels of the Colorado River basin have been extensively altered by the construction and operation of reservoirs. The downstream effects of a reservoir depend not only on the size and operating schedule of the reservoir but also on the location of the reservoir within the basin relative to the major runoff and sediment-contributing areas. Identical reservoirs located at different sites in the Colorado River basin would have very different effects on the channel downstream.

Alteration of flow and sediment transport downstream from reservoirs in the Colorado River basin changes the sediment inflow and outflow to river reaches in a complex longitudinal pattern. Downstream from Flaming Gorge

Reservoir on the Green River, the annual load of sediment transported in the channel immediately downstream from the dam exceeds the supply over a period of years, and the channel is degrading. Between river km 110 and 269 downstream from the dam, the annual load of sediment transported in the channel is approximately equal to the quantity of sediment contributed by tributaries, and the channel is in a quasi-equilibrium condition. Downstream from river km 269, the quantity of sediment contributed by tributaries exceeds the annual sediment load transported in the channel, and the channel is aggrading. The longitudinal sequence is an inevitable result of a significant reduction in flood flows and a relatively large sediment contribution by tributaries to the mainstem channel.

Post-reservoir changes in flow and sediment transport in the Colorado River through Grand Canyon are similar to those that have occurred in the Green River immediately downstream of Flaming Gorge Dam. Annual flood flows have been greatly reduced in magnitude, and the quantity of sand stored within the active channel has been substantially depleted. Two tributaries supply relatively large quantities of water but little flow compared with the Colorado River. The concentration of suspended sediment at the Colorado River near Grand Canyon at a specific discharge has decreased by a factor of 2.3 for commonly occurring flow. Since 1970, the mean annual sediment load of the Colorado River near Grand Canyon has been approximately 11 million tons, which is about the estimated contribution of sediment to the reach between Lee's Ferry and Grand Canyon. Therefore, it appears that currently the supply of sediment to the reach approximately equals the quantity of sediment transported out of the reach.

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5

Limnology of Lake Powell and the Chemistry of the Colorado River

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INTRODUCTION

Lake Powell is a large, dendritic reservoir that fills the Glen Canyon segment of the lower Colorado River. Operation of Lake Powell in turn controls the hydrodynamics of the Colorado River through the Grand Canyon National Park to Lake Mead. The limnology of the reservoir is greatly influenced by (1) the morphometry and geology of the canyon it fills, (2) the design and operation (including the economics of hydropower production) of the dam, (3) the hydrodynamics and chemistry of the inflowing rivers, and (4) climatic variability. The limnology of the reservoir, coupled with dam operations, therefore determines the limnology of the Colorado River downstream from Lake Powell. The purpose of this paper is to review the limnology of Lake Powell in relation to the volume and quality of influent and effluent waters and to discuss the ramifications of reservoir operations on the biophysiology of the Colorado River.

Since our review of the ecology of the Colorado River (Stanford and Ward 1986a–c; Ward et al., 1986), other detailed syntheses have been forth-coming: Graf (1985), Bureau of Reclamation (1987), NRC (1987), Carlson and Muth (1989), and Potter and Drake (1989). Data and interpretations in these lengthy documents are pertinent to this paper. Potter and Drake (1989) is required reading for anyone interested in the developmental history and limnology of Lake Powell, as it summarizes results of a 10-year, multidisciplinary study funded by the National Science Foundation. However, Potter and

Drake (1989) is rather popularly written, and where possible we cite herein the various technical reports and published papers that were forthcoming from the study. Few papers containing original data pertaining to the limnology of Lake Powell and its effects on the riverine environment downstream have been published since the study summarized by Potter and Drake (1989) was concluded in 1980.

MORPHOMETRY AND HYDRODYNAMICS OF LAKE POWELL

Glen Canyon Dam

Glen Canyon Dam is an arch structure with a 107-m (350-ft) base and 476-m (1,560 ft) crest and is composed of 3.6×10^9 m^3 of concrete. It plugs sheer walls of Navajo sandstone bedrock incised over the millennia by the Colorado River. The dam has a crest elevation at 1,132 m (3,715 ft) above sea level, which is 216 m (710 ft) above bedrock and 164 m (583 ft) above the river channel. Eight penstocks discharge a maximum of 943 m^3/s (33,000 ft^3/s) to generators rated for 1.3 MW of hydropower production at full capacity. The penstocks draw water from an elevation of 1,058 m (3,471 ft). The authorized full pool elevation is 1,127.76 m (3,700 ft) above mean sea level. Four bypass tubes and two concrete-lined spillways that release water above 1,122 m (3,680 ft) elevation can pass an additional 7,867 m^3/s (278,000 ft^3/s). This spill volume was needed because flood flows of >5,660 m^3/s (200,000 ft^3/s) have been recorded within Glen Canyon. The dam was closed in September 1963, after a total project construction expenditure of $272 million. Through 1987, gross electrical production exceeded $700 million (Potter and Drake, 1989).

Physical Features of the Reservoir

Lake Powell, named in memory of Colorado River explorer and surveyor J. W. Powell, is impounded by Glen Canyon Dam. Glen Canyon was named by Powell in 1869 for the cottonwood (*Populus fremontii*) glens that dominated the pristine riparian forests on the terraces along the river within the steep-walled canyon. It is the second-largest reservoir in the United States, next to Lake Mead located ca. 250 km downstream on the Colorado River.

Full pool in Lake Powell was first reached on June 22, 1980. At full pool the reservoir yields morphometrics as listed in Table 5-1. Full pool was exceeded by 3 m on July 4, 1983 (only 2.5 m below the crest of the dam) as a result of a period of high flows in the Colorado and Green rivers. Since 1983, the reservoir has filled to capacity every year and has fluctuated only about 8 m annually.

TABLE 5-1 Morphometric features of Lake Powell.

Feature	Value
Surface area (km^2)	653
Volume (km^3)	33.3
Maximum depth (m)	171
Mean depth (m)	51
Maximum length (km)	300
Maximum width (km)	25
Shoreline development	26
Shoreline length (km)	3,057
Discharge depth (m)	70
Maximum operating pool	1,128
Drainage area (km^2)	279,000
Approximate storage ratio (yr)	2

Source: Modified from Potter and Drake, 1989.

Air temperatures range in the Lake Powell area from ca. 5°C (January) to 36°C (August), while the surface water temperatures vary from 6°C (January) to 27°C (August). Average annual precipitation is 14.5 cm, occurring in about equal increments per month. These data summarize a 25-year record at Page, Arizona (Potter and Drake, 1989).

The geology of the reservoir basin is composed of a variety of Jurassic and Triassic sediments. Outcrops of Navajo and Wingate sandstones and the varied shales of the Chinle formation are more notable features of the Glen Canyon. The geology of the Colorado plateau dominates the catchment of Lake Powell and consists of uplifted Tertiary and cretaceous shale and sandstone formations with some areas of Tertiary volcanic extrusion. The Mancos shale formation outcrops over wide areas. The principal feature of the geology relative to the limnology of Lake Powell and its tributary rivers is the omnipresence of calcium, sulfate, and bicarbonate as the predominant dissolution ions within easily eroded substrata (Stanford and Ward, 1986a). Potter and Drake (1989) provide a more detailed review of area geology.

River Discharge and the Water Budget of Lake Powell

Ninety-six percent of the inflow to the reservoir is derived from the catchments of the Colorado and San Juan rivers (Figure 5-1), and 60% of the annual water budget is received in May–July as a result of snowmelt in the headwaters (Irons et al., 1965; Evans and Paulson, 1983).

In 1922 the Colorado River Compact apportioned water allocation based on a virgin (preregulation) flow of 22.2 km^3 at Lee's Ferry. However, the virgin flow is now estimated at 20.72 for the precompact period and 17.52

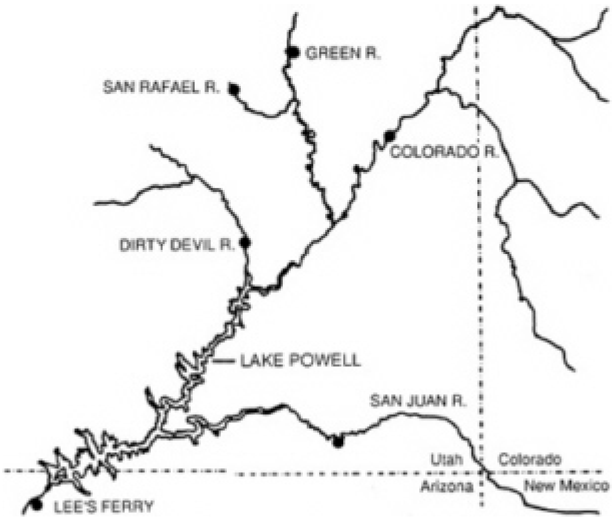

FIGURE 5-1
Lake Powell and tributaries showing sites where flows and water quality have been monitored.
SOURCE: Messer et al., 1983.

since 1922 (Holbert, 1982; Upper Colorado River Commission, 1984). Long-term flows estimated from tree ring data (Stockton and Jacoby, 1976) suggest that the long-term yield of the basin is 16.7 km^3, corroborating the lower virgin flow estimate. Moreover, the tree ring analysis strongly suggests that the Colorado River flows in the 1900s were well above the long-term (ca. 370-year) average. This is important because the Colorado River is regulated to the extent that the legal allocation between the upper and lower basins largely determines the water budget of Lake Powell most years. The Colorado River Compact divided the Colorado River into upper and lower basins at the confluence of the Paria and Colorado rivers, which is located ca. 30 km downstream from Glen Canyon Dam. Note that during the period 1967–1983 only slightly more than the legal allocation to the lower basin (8.9 km^3 = 7.2 million acre-feet) was discharged from Glen Canyon Dam (Figure 5-2). However, only 28.8% of the flow at Lee's Ferry is water previously impounded in the largest upstream reservoirs (Flaming Gorge, Morrow Point, Blue Mesa, and Navajo), owing to consumptive use and downstream water recruitment (Irons et al., 1965). During future low water years, inflow to the reservoir probably will be insufficient to meet the legal allocation downstream and Lake Powell will have to be drafted to make up the difference. In essence, Lake Powell buffers delivery of water from the upper basin to the lower basin.

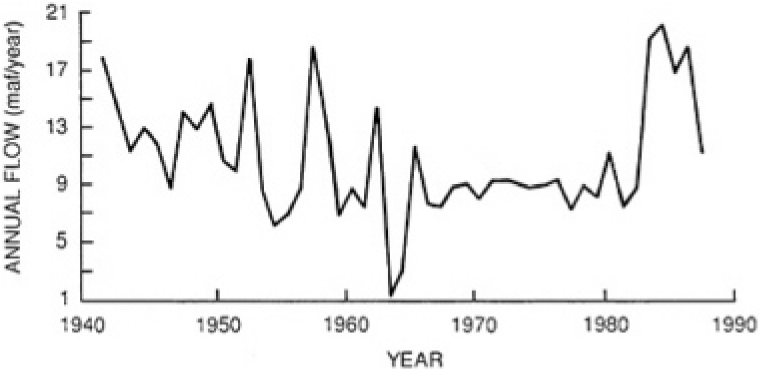

Figure 5-2
Annual flows in the Colorado River at Lee's Ferry, located 24 km downstream from Glen Canyon Dam.
Source: Modified from Bureau of Reclamation, 1989.

In the decade of the 1980s, flows in the Colorado River system were generally well above the long-term average (Figure 5-2) and allocation of water to fulfill legal rights was not a problem. Indeed, flows during the spring freshet in 1983 were the highest on record, owing to late season snow accumulation, accelerated snowpack ablation, and high initial reservoir levels (Vandivere and Vorster, 1984). Streamflow forecasts also were not suitable for the climatic extremes in the basin in 1983 (Rhodes et al., 1984; Dracup et al., 1985). Reservoir elevation in Lake Powell exceeded full pool by 3 m during July 1983, and the dam operators were forced to bypass flood flows. The next year, 1984, also generated extreme runoff in the upper basin, and flood flows were again bypassed. Considerable damage to riverine environments downstream occurred, including severe erosion of beach and terrace environments within the Grand Canyon National Park.

Ground water inflows to Lake Powell apparently are related to aquifers in the Navajo sandstone, which is associated with the major surficial features of the reservoir and its dam (Blanchard, 1986). Quantities of ground water inflow are not known but are probably insignificant in relation to fluvial sources and bank storage.

The Lake Powell water budget is dominated by inflow from the Colorado and San Juan rivers, although a major volume is included in bank storage and evaporation (Table 5-2). Bank storage increases over the life of a reservoir (Langbein, 1960). From 1964 to 1976, an estimated 10.5 km^3 went into bank storage at Lake Powell, for an average of 740,000 m^3 $year^{-1}$. These storage rates are consistent with the measured porosity of the Navajo sandstone (Potter and Drake, 1989). Evaporation was estimated at 6.2 × 108 m^3 $year^{-1}$ or about 180 cm/year, based on measures in 1973–74 (Jacoby et al., 1977; but see Dawdy, this volume). The difference between riverine inflow and the losses given in Table 5-2 is the volume of water stored annually within the reservoir as it is filled and is fairly consistent with the reservoir's elevation volume trend for the period.

The volume stored annually is determined from runoff delivered by the rivers to Lake Powell in excess of the release mandate of the Colorado River Compact for the lower basin. The initial filling of the reservoir was accomplished a decade sooner than predicted from average flows, as a result of high flows during the 1980s. This again brings out the point that in future dry years lower basin allocation could cause Lake Powell to be drafted well below the volume that may be supplied by runoff in excess of reservoir storage from the upper basin. Hence, a major problem for the legal pundits involves determination of which reservoirs, if any, in the system have filling priority over Lake Powell. For the limnologist it means that prediction of pool levels in the reservoir and flows downstream require greater model

TABLE 5-2 Water budget for Lake Powell based on average data for the period 1964–1975, the period when the reservoir was filling. Data are km3.

River Inflow	
Colorado River	10.6408
San Juan River	1.6881
Losses	
Bank Storage	.7404
Evaporation[1]	.6170
Outflow measured at Lee's Ferry	10.0818
Difference	
Reservoir storage	2.2471

[1] corrected for precipitation and based on reservoir two-thirds full

Source: Modified from Jacoby et al., 1977.

ing sophistication than currently exists. Without a verified hydrological model, predicting ecological responses to regulation is problematic.

The presence of Lake Powell has vastly altered the hydrograph of the river downstream of the dam. Indeed, Lake Powell hydropower operations effectively control downstream hydrodynamics (Table 5-3). Except in years of high-volume inflow to the reservoir (e.g., 1983 and 1984; Figure 5-3), flow seasonality is absent (e.g., 1982; Figure 5-3), as a result of reservoir storage. Flows from the dam fluctuate between 85 and 570 m^3 (3,000–20,000 ft^3) in a "yo-yo" fashion over short time periods (days) in response to the economics of hydropower (Figure 5-3).

TABLE 5-3 Hydrological, thermal, and sediment transport characteristics of the Colorado River below Glen Canyon Dam based on the 1941–1977 period of record.

Measurement	Lee's Ferry[a]		Grand Canyon[b]	
	Pre-dam	Post-dam	Pre-dam	Post-dam
Daily average flow equaled or exceeded 95% of the time (m^3/s)	102	156	113	167
Median discharge (m^3/s)	209	345	232	362
Mean annual flood (m^3/s)	2434	764	2434	792
Annual maximum stage (m)				
Mean	5.04	3.56	6.89	4.79
Standard deviation	0.96	0.17	0.35	0.15
Annual minimum stage (m)				
Mean	1.76	1.46	0.46	0.70
Standard deviation	1.40	0.23	0.85	0.45
Annual average				
temperature (°C)	10	10	11	12
Range (°C)	2-26	7-10	2-28	5-15
Mean sediment concentration (mg/liter)	1500	7	1250	350
Sediment concentration equaled or exceeded 1% of the time (mg/liter)	21000	700	28000	15000

[a] 24 km downstream from Glen Canyon Dam

[b] 165 km downstream from Glen Canyon Dam

Source: Dolan et al., 1974; Paulson and Baker, 1981; Petts, 1984; U.S. Geological Survey, unpublished data.

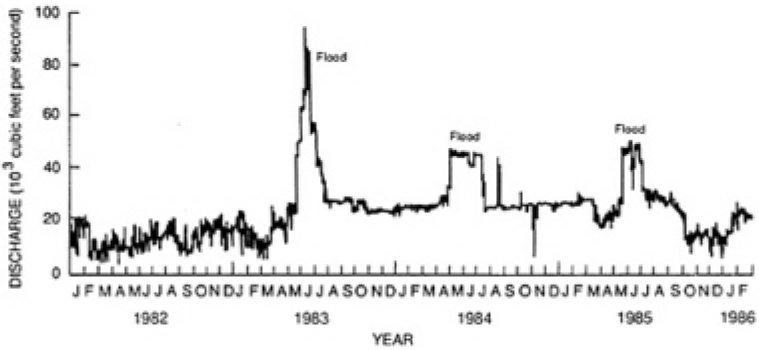

FIGURE 5-3
Inter- and intrayear variation in discharge of the Colorado River at Lee's Ferry as a consequence of hydropower and flood control operations at Glen Canyon Dam for the period 1982–1986.
SOURCE: Modified from Potter and Drake, 1989.

Seasonal Stratification

Lake Powell is warm (i.e., the annual heat budget is 40 kcal/cm^2), monomictic, and intensely stratified during most of the year. The intensity of seasonal stratification is determined by temperature, salinity, suspended solids, depth of the water column, and extent of riverine advection. Indeed, the reservoir mixes convectively only during the winter cooling period, when pelagic temperatures are 10°C (Paulson and Baker, 1983a) and mixing does not extend to the bottom (Johnson and Merritt, 1979). Lack of convective circulation is also partly due to the fact that 53% of the entire shoreline is vertical cliff (Potter and Pattison, 1976), which reduces wind-driven circulation within the water column of the reservoir. Overflow or interflowing density currents from the Colorado River occur annually in relation to the intensity and duration of the freshet. The relatively warmer and less saline waters from the freshet form a pycnocline between colder and more saline waters on the bottom of the reservoir. This over-or interflowing wedge of water from the rivers moves down the reservoir, gradually thinning as it reaches toward the dam by late summer (Gloss et al., 1980). Advection, therefore, mechanically sets the depth and extent of seasonal thermal stratification (Johnson and Merritt, 1979).

Because of the relatively shallow morphometry and substantial effects of river inflow, the upper reaches of the reservoir are dominated by advective mixing. Average retention time for reservoir volume north of Bullfrog Bay in the San Juan arm is less than 8 months (Potter and Drake, 1989).

A widespread halocline occurs in Lake Powell. Because of lack of wind circulation, there is a monimolimnion from the dam to the upper reaches of the reservoir. Convective circulation penetrates only to about 60 m (Johnson and Merritt, 1979). However, bottom water remains aerobic (i.e., >3 mg/liter dissolved oxygen), owing primarily to advective circulation generated by saline underflows from the Colorado and San Juan rivers during low winter discharge (Johnson and Page, 1981).

Metalimnetic oxygen depletion (negative heterograde profile) occurs virtually lakewide in the late summer (Stewart and Blinn, 1976; Johnson and Page, 1981; Sollberger et al., 1989); anoxia presumably is caused by decomposition of senescent phytoplankton that accumulates on the chemocline after settling from the mixolimnion (Hansmann et al., 1974; Johnson and Page, 1981). Metalimnetic oxygen stagnation begins in the bay mouths and temporally develops toward the dam. Convective circulation reduces oxygen depletion in early winter (Johnson and Page, 1981; Sollberger et al., 1989).

Because of reoxygenation by winter river underflows noted above and trapping of organic matter in the metalimnion, the monimolimnion remains aerobic. This limits nutrient mobilization from the sediments, and nutrients released by mineralization are not returned to the epilimnion due to the lack of convective circulation (Gloss et al., 1980, 1981). Calcite precipitation also may scavenge dissolved substances, particularly phosphate, via adsorption (Reynolds, 1978). Moreover, the depth of convective circulation and halocline formation in Lake Powell is marked by a strong withdrawal current at ca. 30–50 m (Johnson and Merritt, 1979) which removes epilimnetic nutrient loads (Gloss et al., 1980). Thus, there is a persistent nutrient deficiency in the euphotic zone. Bioproduction in Lake Powell is phosphorus limited and dependent on seasonal advective nutrient renewal via the spring overflow of the river turbidity plume (Gloss, 1977; Gloss et al., 1980).

Edinger et al. (1984) describe a longitudinal and vertical hydrodynamic and transport model called LARM. This model allows study of seasonal circulation, heat, and salinity transport and predicts equilibrium relationship over an entire reservoir volume. Thus, changes in solute concentrations, due to precipitation and dissolution, may be evaluated by using LARM.

PARTICULATE AND DISSOLVED SOLIDS DYNAMICS

Long-term data bases that describe the temporal chemistry of the rivers above and below Lake Powell (i.e., the sites in Figure 5-1) are maintained by the U.S. Geological Survey in their WATSTORE file. Flow, total dissolved solids (TDS) and specific conductance data are evaluated annually to document trends as related to salinity control projects within the Colorado

River basin (Bureau of Reclamation, 1989). These long-term data bases are readily available in electronic media and have been used extensively in studies of the biogeochemistry of Lake Powell (e.g., Messer et al., 1983; and Edinger et al., 1984).

Suspended Sediment

Stanford and Ward (1986a) characterized the Colorado River as one of the most erosive in the world. The virgin river was very turbid except at low flows, and sediment dynamics greatly influenced the riverine ecology, both within the river channel and in its floodplains and terraces. Most of the historical and current sediment load is derived from erosion of the soft sedimentary formations of the Colorado plateau (Irons et al., 1965).

Construction of mainstem dams has vastly altered the sediment transport processes of the river. Lake Powell receives 40–140 million tons of suspended sediment annually from its tributaries. Upstream dams on the Gunnison, San Juan, and Green rivers have not reduced the load (Mayer and Gloss, 1980), again substantiating the influence of the middle reaches of the Colorado, Green, and San Juan rivers on the water and sediment supply to Lake Powell (Irons et al., 1965). Retention of fluvial sediments within Lake Powell reduces the suspended sediment load in the Grand Canyon segment of the Colorado River by 70–80% (Evans and Paulson, 1983; Table 5-3). About 25% of the historic sediment load at Lee's Ferry was derived from side flows to Lake Powell such as the Dirty Devil and Escalante rivers (Potter and Drake, 1989). The Little Colorado River, which joins the Colorado River within the Grand Canyon, and the Paria River can contribute heavy sediment loads to the river during short-term spates, but the sediment load of the Colorado River is now virtually controlled by retention in Lake Powell.

The fluvial sediments entering Lake Powell are dominated by the montmorillinite clay lattice and have an average in situ bulk density of 1.5 with a mean grain density of 2.65 g/cm^3 dry mass, based on analysis of cores (Potter and Drake, 1989; but see Kennedy [1965] and Mayer [1973] for clay mineralogy of Colorado River suspended sediments). Mass balance calculations show that 60×10^9 m^3 of sediment is stored on the bottom of the reservoir annually. Most of the fluvial sediments are presently deposited near the mouths of the Colorado and San Juan rivers. Maximum sedimentation rates were better than 3 m/year through 1974 within the Colorado River arm and about 2 m/year within the San Juan arm of the reservoir. Over 50 m of sediment has accumulated near the mouth of the Colorado River and over 15 m has accumulated on the San Juan River delta as determined from 1987 sonar profiles presented by Potter and Drake, (1989). Bank slumping has contributed additional sediment at various sites on the reservoir shoreline, particularly in areas of sidehill dunes and steep gradient soils. Rockfalls from partially inundated cliff walls have also occurred. Sedimentation rates determined from echo soundings suggest that the reservoir basin will fill completely in about 700 years (Potter and Drake, 1989).

Riverine suspended sediments in the smallest size fraction (e.g., 10–30 um may be transported far into the pelagic zone of the reservoir). These fine sediments are nutrient rich, relative to dissolved constituents within the water column, and fertilize the reservoir. However, the sediment-laden river waters usually interflow through the reservoir because advectively circulated flood waters are typically colder and more dense than the upper portions of the water column (Gloss et al., 1980, 1981).

Nitrogen, Phosphorus, and Silica

Because of the patterns of seasonal stratification described above, nutrients such as nitrogen, phosphorus, and silica are most uniformly distributed within the water column of Lake Powell during the winter and early spring. Advective circulation, driven by the annual spring freshet, establishes firm stratification and loads the epilimnion with nutrients. Phytoplankton production increases, thereby depleting nitrate, silicate, and soluble reactive phosphorus within the water column during the summer growing season. Since the epilimnion is essentially isolated by thermal and haline stratification, much of the microbial biomass produced within the epilimnion sinks toward the bottom. This is corroborated by oxygen depletion in the metalimnion, where biomass deposited on the pycnocline begins to decompose, creating the oxygen demand described above. As primary production increases, calcite precipitation also may increase, which in turn may allow additional phosphorus loss as a function of adsorption to calcite particles. Moreover, soluble and particulate nutrients are lost via the withdrawal current from the dam. Nutrients entrained in the hypolimnion or bottom sediments are not regenerated within the water column, owing to the lack of convective circulation and an inverse redox gradient (Gloss et al., 1980).

Thus, the reservoir is a nutrient sink, especially for phosphorus. Flow-weighted mass balance calculations provide retention coefficients of .74 for dissolved phosphorus and .96 for total phosphorus (Gloss et al., 1981; Miller et al., 1983). Total nitrogen is more conservative; Gloss et al. (1981) estimated 9% retention. The nitrogen load is ca. 47% organic N and 45% nitrate, and inflow and outflow values of the various forms of nitrogen are similar. The retention coefficient for silica is estimated at .14, with losses attributed to uptake by diatoms and subsequent sedimentation (Gloss et al., 1981).

Over 95% of the fluvial phosphorus reaching Lake Powell is particulate, associated with clays in the suspended sediments (Gloss et al., 1981; Evans and Paulson, 1983). Thus, most of the load is sedimented within the reservoir basin. However, Mayer and Gloss (1980) estimated that about 20–30 μg/liter of inorganic phosphorus may be maintained within Colorado River water by progressive desorption from the clay particles. Since microbial production within the water column appears to be phosphorus limited and inversely related to the concentration of dissolved nutrients (i.e., production increases until nutrients are depleted; Gloss, 1977), apparently bioproduction in Lake Powell is directly related to the intensity and duration (spatial and temporal) of the enriched spring freshet event.

Some bays apparently are locally eutrophied, relative to the pelagic areas of the reservoir, by concentrated human activities (Hansmann et al., 1974).

Bioavailability of Particulate Phosphorus

Because of the importance of the phosphorus budget to lakewide bioproduction, the question of how much of the incoming phosphorus load is actually biologically labile or bioavailable is especially relevant. As noted above, Colorado River suspended sediments may desorb 20–30 μg/liter soluble reactive phosphorus (SRP), as determined from sequential measures of SRP after progressively placing suspended sediments in fresh aliquots of filtered lake water (Mayer and Gloss, 1980; Gloss et al., 1981). SRP is generally thought to be 100% bioavailable (Wetzel and Likens, 1979). Thus, suspended sediments are clearly an important source of bioavailable phosphorus. Using NaOH extractions of sediments obtained from Colorado River water, Evans and Paulson (1983) determined that only 7–19% (mean, 11.2%) of the particulate phosphorus is bioavailable. However, NaOH extractions may not provide an accurate estimate of bioavailable phosphorus since results are not often comparable to estimates derived from algal assays and kinetic experiments (Ellis and Stanford, 1988). Using algal bioassays and stoichiometric analyses of whole water, Watts and Lamarra (1983) determined that 21 and 49% of total phosphorus in Colorado River water at Moab Bridge in September 1978 and October 1978 was bioavailable; most of the extractable phosphorus was in the form of calcium-bound phosphorus, involving phosphorus adsorption on a lattice of the calcite crystal or coprecipitation of phosphorus during calcite formation. Although SRP concentrations are typically low in Colorado River water (usually <10 μg/liter), primary productivity of the river water does not appear to be nutrient limited; rather, Watts and Lamarra (1983) found an inverse relationship between turbidity and primary production, suggesting that the in situ light regime and concentration of calcite-bound phosphorus may interact to control algal production. Swale (1964) and Lund (1969) had similar conclusions for the calcareous River Wye in England.

On the basis of these data and interpretations, the issue of bioavailability of particulate phosphorus derived from the spring freshet is not explicitly worked out. It is apparent that bioproduction is stimulated by the freshet event, but only a small percentage of the sediment-bound phosphorus is actually mobilized by the food web. It is not surprising that Lake Powell does not fit the empirical models used to predict eutrophication from nutrient loading (Labough and Winter, 1981; Mueller, 1982). Indeed, on the basis of the net flow-weighted phosphorus budgets, which apparently vary from less than 2,060 to greater than 7,295 million tons/year as a function of the freshet volume, one would expect Lake Powell to be hypereutrophic (Gloss et al., 1981). Clearly that is not the case, because >95% of the annual phosphorus load is associated with riverine sediments (Evans and Paulson, 1983) that settle to the bottom of the reservoir before large amounts of the particulate phosphorus are either chemically desorbed or actively mobilized by microbiota (see Ellis and Stanford, 1988).

Salinity

Total dissolved solids (TDS) in Lake Powell are dominated by SO_4^{2-}, HCO_3^-, Ca^{2+}, and Na^+ ions (Table 5-4). Calcium and sodium sulfates dominate the riverine TDS load, owing to the predominance of gypsum substrata within the catchment (Stanford and Ward, 1986a). TDS concentrations are extremely dynamic over time (i.e., similar to the pre-1960s period in Figure 5-3)

TABLE 5-4 Composition of the major ions contributing TDS in the Colorado River at Lee's Ferry compared to Lake Powell water discharged from Glen Canyon Dam.

	Lee's Ferry 1948–1962		Lee's Ferry 1948-1962 (Corrected for Evaporation)		Glen Canyon Dam Discharge, 1972–1975	
Ion	μE/liter	mg/liter	μE/liter	mg/liter	μE/liter	mg/liter
Ca	4,012	81.8	4,249	86.6	3,607	73.6
Mg	1,990	24.2	2,107	25.6	2,051	24.9
Na	2,975	68.4	3,151	72.4	3,293	75.7
K	107	4.2	113	4.5	105	4.1
HCO3	3,098	189.0	3,280	200.0	2,506	159.0
SO_4	4,538	218.0	4,806	231.0	5,016	241.0
Cl	1,323	46.9	1,401	49.7	1,441	51.1
Total		633		670		629

Source: Gloss et al., 1981.

in the main tributaries of Lake Powell, as a consequence of flow variability. Freshet flows tend to dilute the dissolved solids concentrations. Average concentrations are three times higher in the San Rafael River (Figure 5-4), but average annual flow-weighted loads are highest in the Colorado River. Because of the stabilization of flow by the dam, the salinity of the Colorado River at Lee's Ferry has been fairly uniform; the gradual decline in the decade of the 1980s (Figure 5-5) is apparently due mainly to dilution caused by above-average flows, calcite precipitation in Lake Powell, and a decrease in gypsum dissolution from the bed of Lake Powell (Paulson and Baker, 1983b).

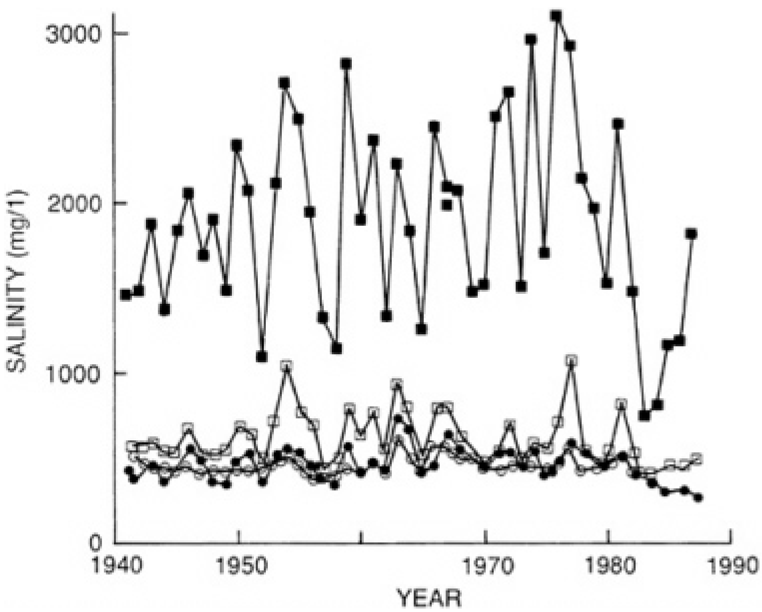

FIGURE 5-4
Average annual concentrations of TDS derived from daily measurements at the tributary sites shown in Figure 5-1 for the period 1941–1987.
SOURCE: Bureau of Reclamation, 1989.

The Lake Powell TDS budget has been a primary study topic because of the general conception that evaporation and dissolution of bed substrata in reservoirs is purported as a primary cause of increasing salinity in the Colorado River. (Salinity in the Colorado River at Imperial Dam increased from 380 mg/ liter during pristine times to 825 mg/liter by 1975 [Gardner and Steward, 1975]. Salinity trend models indicate that additional water diver sions may increase salinity to >1,150 mg/liter by the end of the century [Kleinman and Brown, 1980; Law and Hornsby, 1982]) Indeed, Gloss et al. (1980) noticed a slight increase in $S0_4$ at Lee's Ferry after impoundment of Lake Powell and attributed it to gypsum dissolution that should decrease in time. On a mass balance basis and under steady-state conditions, evaporation and leaching of sulfate from the reservoir bed apparently could account for an annual increase in salinity of ca. 40 mg/liter below the dam. However, this increase is apparently offset by appreciable calcite precipitation. Thus, pre- and post-dam salinities in the Colorado River at Lee's Ferry are about the same (Table 5-4) (Reynolds and Johnson, 1974; Gloss et al., 1980). However, Paulson and Baker (1983b) gave flow-weighted averages for common ions and TDS for the period 1970–1979; they estimate annual calcite ($CaCO_3$), gypsum ($CaSO_4$) and halite (NaCI) precipitation rates in Lake Powell to be 23 (9), 16 (5), and 5 mg/liter (Ca^{2+} concentration in parentheses) on the basis of ion budgets. These loss rates are high enough to partially account for the decline in river salinity in recent years (Figure 5-5). On the other hand, Messer et al. (1983) calculated a salinity mass balance based on data for the period 1941–1975 which left 8.1 × 10^6 million tons of salt or 8% of the calculated input either in bank storage or lost to the sediments by some biogeochemical removal process (i.e., precipitation or coprecipitation with inorganic particles, such as clays), coagulation (involving polysaccharide fibrils of microbes), and bioassimilation (by microbiota)). Assuming bank storage of 11 × 10^9 million tons and flow-weighted TDS of 569 mg/liter, 6.2 × 10^6 million tons of salt was bank stored, leaving only 1.9% that could have been removed by biogeochemical processes. Messer et al. (1983) considered their budget to be conservative, since bed dissolution

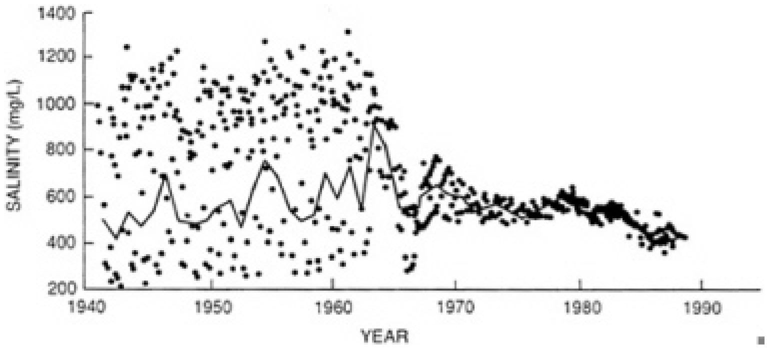

FIGURE 5-5
Time series trend for salinity in the Colorado River at Lee's Ferry.
SOURCE: Bureau of Reclamation, 1989.

processes were not included. They concluded that massive biogeochemical salt removal (i.e. calcite precipitation) could not have occurred. This conclusion was corroborated by the LARM hydrodynamics model (Edinger et al., 1984), which showed that 1% of the salt load could precipitate in the epilimnion annually, but redox conditions in the lower water column were sufficient to resolubilize the precipitant. We note that all of the mass balance calculations are based on measurements of river discharge and TDS well upstream from Lake Powell (Figure 5-1) and that many of the side flows into the reservoir are not monitored at all. Given the size of the reservoir and the inaccuracies of loading estimates, it is doubtful that the actual impact of calcite precipitation on salinity trends in the Colorado River will be verified from mass balance calculations. That the rate of calcite precipitation in Lake Powell is influenced by fluvial salt loading, bed dissolution of $CaSO_4$, phytoplankton productivity, and polyphenol inhibition (Reynolds, 1978) seems conclusive.

Heavy Metals and Other Pollutants

Potter and Baker (1989) noted that filling of the reservoir provided a unique opportunity to examine bioamplification of heavy metals resulting from erosion of natural geologic deposits. Indeed, natural weathering of the complex geologic deposits within the Colorado plateau contributes a variety of metals to Lake Powell, mostly in association with fluvial sediments (Graf, 1985).

The mercury story is best documented. Forty-percent of the mercury load (2,200 kg/year) is derived from the Green River catchment, where the source rocks appear to be the Chinle and Morrison formations (Graf, 1985). Mercury concentrations in Lake Powell sediments average 30 parts per billion (range, 5–53) (Standiford et al., 1973); in the turbid upper reaches of the reservoir water column concentrations approach 6 parts per billion, which Blinn et al. (1977a) showed to be inhibitory to phytoplankton primary productivity. Tompkins and Blinn (1976) assayed mercury effects on growth of two of the common planktonic diatoms and found that *Fragilaria crotonensis* was considerably more sensitive than *Asterionella formosa*. Concentrations in fish tissues ranged from 5 to 700 μg/mg dry mass, suggesting a ca. 43-fold increase relative to average concentrations in the catchment substrata (Potter et al., 1975).

Relatively high selenium concentrations have been observed in Colorado River tributaries draining Mancos shale formations (Stanford and Ward, 1986a). Relatively high concentrations were observed in the larger fishes of Lake Powell (Potter and Drake, 1989) and warrant further work, as selenium may inhibit egg production in squawfish and other native fishes of the Colorado River.

Heavy metal contamination within the headwater reaches of the Colorado River has been a concern for years because of hard rock mine effluents in many locations (e.g., Gunnison, Dolores, and San Miguel rivers). How much of this contamination reaches Lake Powell is unknown. Heavy metals associated with emissions from coal-fired generating plants in the Lake Powell area have been shown to reduce photosynthesis and respiration in microcosms containing water from Lake Powell (Medine et al., 1980; Medine and Porcella, 1980). However, Potter and Drake (1989) concluded that mercury and selenium were the only heavy metals reaching Lake Powell in sufficient concentrations to affect the food web.

Radioactive pollutants enter the reservoir from several sources: (1) naturally associated with basin geology; (2) from waste ponds and heaps located at various sites (e.g., San Miguel River); and (3) in association with coalfired generating plants in the basin (Graf, 1985). The impact within the food web is apparently unknown.

LAKE POWELL FOOD WEB

Phytoplankton

Gloss et al. (1980) reported primary productivity in the reservoir of 2–60 mg of ^{14}C m^{-3} day^{-1} during the summers of 1975 and 1976. Values varied an order of magnitude spatially during a given sampling period. Maximum productivity occurred between 1 and 3m in depth. Hansmann et al. (1974) reported that in 1971 the highest productivity (1,066 mg of C m^{-2} day^{-1}) occurred in July and the lowest (33 mg of C m^{-2} day^{-1}) was measured in February. Yearly productivity was estimated at 184 g of C m^{-2}. Blinn et al. (1977a) reported similar values. Because of the variable amounts of sediments suspended in the water column, productivity varies greatly within the reservoir in relation to light attenuation (Blinn et al., 1977b). Chlorophyll concentrations in the water column averaged 5 µg/liter near the Colorado River and 1.5 µg/liter lakewide during 1982–1983 (Paulson and Baker, 1983a) and 1987–1988 (Sollberger et al., 1989).

Seasonal phytoplankton succession in Lake Powell involves a spring diatom pulse (*Fragilaria crotonensis* and *Asterionella formosa*), a diverse summer community (*Dinobryon sertularia* and Chloroccocales), a late autumn pulse of diatoms (*Synedra delicatessima* var. *augustissima*) and dinoflagellates, and no abundant winter forms (Stewart and Blinn, 1976; Blinn et al., 1977b). The spring pulse yielded chlorophyll values of 1.8 µg/liter in the downstream end of the reservoir (Sollberger et al., 1989). This vernal diatom bloom is common in large oligotrophic lakes (e.g., Flathead Lake, Montana) and does not suggest extreme or abnormal nutrient loading. Indeed, bluegreen blooms do not occur in Lake Powell as commonly occur in large upstream impoundments (e.g., Flaming Gorge Reservoir on the Green River) (Miller et al., 1983). This is undoubtedly due to lower concentrations of bioavailable nutrients in Lake Powell and the fact that thermal and haline stratification promotes nutrient loss via withdrawal and hypolimnetic entrainment. Relatively high salinity does not seem to play much of a role, although indigenous Lake Powell diatoms are apparently more tolerant of salinity additions than are standard bioassay test algae (Cleave et al., 1981). On the basis of the general nutrient regime and importance of allochthonous sediments, we suspect that picoplankton (i.e., cells <10 μm in size) are probably very important in Lake Powell, but the size distribution of the plankton has apparently not been investigated.

Zooplankton

Stone and Rathbun (1969) reported that *Daphnia, Cyclops,* and *Diaptomus* were dominant zooplankters with densities that varied between 15 and 100 individuals per liter in the upper 30 m of the water column. Densities were higher in the summer and at the upper end of the reservoir. At the downstream end, samples rarely exceeded 20 per liter and did not vary much seasonally.

In a more detailed study conducted in 1987–1988, Sollberger et al. (1989) found 36 species (8 *Copepoda*, 13 *Cladocera*, and 15 *Rotifera*); *Cyclops bicuspidatus*, *Mesocyclops edax*, and *Diaptomus ashlandi* were the most common copepods, whereas *Bosmina longi-rostris, Daphnia galeata* and *D. pulex, Collotheca* sp., *Polyarthra* sp., and *Syncheata* sp. were the most common cladocerans and rotifers. Copepods were the most abundant group. Densities of total zooplankton in the water column were normally 20 per liter and never exceeded 50 per liter, with the higher concentrations occurring in the upper 20 m of the water column during April (average densities ranged from 3 to 26 per liter within the upper 40 m). These data are surprisingly similar to the counts made two decades earlier by Stone and Rathbun (1969), suggesting little if any decline in productivity. Density of zooplankton was inversely related to chlorophyll content. Densities declined through the summer, perhaps as a result of predation. No significant vertical migration was observed, and zooplankters primarily inhabited the epilimnion. The lipid-ovary index was generally <0.5 for the *Daphnia*, and egg ratios were <0.2, indicating that populations were food limited most of the year.

Benthos

Artificial substrata (plastic trees) placed in the littoral zone of Lake Powell were colonized by 69 diatom taxa, 6 of which made up 65–94% of the periphyton community numerically. Maximum periphyton occurred in spring and fall. Macroinvertebrate communities colonizing the substrata were dominated by chironomids, with *Physa*, jellyfish (*Craspedacusta sowerbyi*), water mites, and damselflies occasionally present (Potter and Louderbough, 1977).

Potter and Pattison (1976) used a bilge pump and scuba equipment to collect natural benthic biofilms and found an average of 2.14 g/m^2 with an average chlorophyll content of 352 mg/m^2, or about ten times greater than average concentrations in the water column. In doing this work they noticed that wood rat (*Neotoma*) middens, submerged upon closure of the dam, could be identified by plumes of benthic periphyton. The benthic algae was apparently stimulated by nutrients leached from the middens.

Since so much of the shoreline is near vertical cliffs (54%), the high water line is marked by epilithic biofilms. This biofilm is oxidized during the drawdown period, leaving a white bathtub ring that grades into characteristic black streaks on red sandstones. The latter is caused by cementing of clays with oxides and hydroxides resulting from the oxidation of minerals and organics by mixotropic bacteria (Dorn and Oberlander, 1982).

Fishes

Fisheries in Lake Powell are derived from a hodgepodge of native and introduced species. The introduced species predominate. Indeed, the status of the endemic big river fishes (e.g., squawfish, humpback chub, and razorback sucker; Stanford and Ward, 1986c; Carlson and Muth, 1989) that inhabited Glen Canyon prior to impoundment is unknown. Persons and Bulkley (1982) reported that *Dorosoma petenense* (threadfin shad) were primary food items in guts of *Merone saxatalis* (striped bass) that spawned in the mixing zone of the Colorado River. They observed that none of these reservoir fish moved very far upstream, and no evidence of predation on endemic fishes was found. Dynamics of the pelagic shad and striped bass populations appear to be the most economically significant aspect of the Lake Powell fisheries. Other bass (*Micropterus salmoides, M. dolomieui*), channel cat (*Icralurus punctatus*), northern pike (*Esox lucius*), walleye (*Stizostedion verreum*), crappie (*Pomoxis nigromaculatus, P. annularis*), and sunfishes (*Lepomis cyanellus, L. gulosus, L. macrochirus, L. microlophus*) are common, especially near shore. Rainbow trout (*Onocorhynchus mykiss*) and brown trout (*Salmo trutta*) occupy cooler waters in the lower end of the reservoir.

Quantitative food web relationship for the fishes relative to reservoirwide plankton production have not been established. The trophic status of Lake Powell appears to be oligotrophic, on the basis of primary production, average chlorophyll content, and the depressed nutritional status of the zooplankton. Thus, Lake Powell fisheries should not be expected to be very productive, and populations may fluctuate as bioproduction of the plankton waxes and wanes in response to riverine nutrient loading and drafting for hydropower and downstream water demands. Fluctuations may also manifest as a consequence of angler harvest, disease, poor recruitment (e.g., related to reservoir operations), and/or introduction of new species (e.g., rainbow smelt [*Osmerus mordax*], a pelagic planktivore, may be introduced in an attempt to supplement forage for striped bass and other piscivores; Courtenay and Robins, 1989; Gustaveson et al., 1990).

Indeed, the food web currently appears to be destabilized. Densities of threadfin shad have decreased from >600 adult fish per standardized trawl in 1977–1978 to 0 in 1989. Concomitantly, the mean size of striped bass declined from 620 mm (24 inches) to 348 (14 inches); the mass/length rates declined from 1.6 to 1.0. Formerly abundant walleye and largemouth bass populations have also declined (Gustaveson et al., 1990). Destabilization of the food web appears to have occurred from the top down, since the fertility of the reservoir seems to have changed very little and zooplankton crops are about the same today as in 1969 (see above). The striped bass cohorts that were dominated by large-bodied individuals in the late 1970s probably were very productive, and subsequent high recruitment of juveniles may have gradually reduced the shad forage. Moreover, juvenile striped bass are able to forage in the warm upper layers of the reservoir (>10 m) where shad densities are greatest; adult bass are more stenothermic and habitually reside in deeper waters (Larry Paulson, personal communication). Rainbow smelt prefer colder waters and could be good forage for the larger bass cohorts. However, the net growth potential of the Lake Powell food web is limited because of its oligotrophic status, and productivity can be packaged only in so many ways. The bass-shad relation could be long-term cyclic and/or strongly influenced by angler harvest. Introduction of another planktivore may only further destabilize the food web and produce unanticipated negative effects (see Moyle et al., 1986). Moreover, smelt may rapidly disperse above and below the reservoir, perhaps compromising recovery of the endangered native fishes and creating a plethora of other problems (Courtenay and Robins, 1989).

Riparian Systems

The flora of the xeric uplands of the Lake Powell area is characterized by patches of pinon-juniper (*Pinus edulia-Juniperus spp.*) and a wide variety of desert shrubs, such as blackbrush (*Coleogyne ramosissima*), Mormon tea (*Ephedra spp.*), sagebrush (*Artimesia spp.*), shrub oak (*Quercus* spp.), and *Yucca galeata*. These trees and bushes occur commonly on the rim and flanks of Glen Canyon and, prior to impoundment, graded into terrace flora that included deep-rooted shrubs (such as four-winged saltbrush [*Atriplex* *canescens*], greasewood [*Sarcobatus* spp.], rabbitbrush [*Chrysothammus* spp.] and squawbush [*Rhus trilolata*]) which formed irregular patches. The riparian flora was mainly large galleries of Fremont cottonwood (*Populusfremontii*) interspersed with patches of willows (*Salix* spp.), hackberry (*Celris reticulata*), gambel oak (*Quercus gambeli*), saltgrass (*Distichilis* spp.), slender dropseed (Sporobolus spp.), and clumps of tall reed (*Phragmites* sp.). Many species of birds and mammals seasonally inhabited these plant communities (Stanford and Ward, 1986a).

Potter and Drake (1989) provided an excellent summary of the shoreline vegetation and associated changes as impoundment ensued, based on original work by Potter and Pattison (1977). The main conclusion is that most of the preimpoundment riparian forests and other streamside plants are gone and availability of riparian habitat is limited within the reservoir landscape. Only 3% (ca. 1,000 hectares) of the shoreline is sandy and aggraded. These areas have been uniformly invaded by exotic saltcedar (*Tamarisk chinensis*). The few cottonwood seedlings that managed to root in a few places were largely eliminated by dense and fast-growing saltcedar stands. Saltcedar remain very viable throughout the upper drawdown zone of the reservoir and are very tolerant of flooding. The lower drawdown zone is colonized by Russian thistle (*Salsola kali*).

INFLUENCE OF LAKE POWELL ON ENVIRONMENTS DOWNSTREAM

Lake Powell as a Heat and Materials Sink

River temperatures at Lee's Ferry in summer are on the average 11°C colder than prior to regulation because the dam discharges water from the metalimnion of the reservoir. Winter temperatures in the post-dam river average 8°C warmer than pre-dam conditions (Table 5-3). Consequently, there is little or no seasonality to the river temperatures until insolation and side flows begin to reestablish the riverine heat budget within the Grand Canyon.

Materials balance calculations show that most of the sediments and most of the phosphorus and other metals entering the reservoir are retained in the basin either in the profundal waters and sediments or in bank storage. Thus, the reservoir sequesters the solids load of the Colorado River. On the other hand, soluble phosphorus, nitrate, and silicate are depleted within the epilimnion by the withdrawal current (see above). Therefore, dam tailwaters are continually transparent and loaded with labile nutrients. These conditions persist downstream into the Grand Canyon and greatly promote bioproduction within the riverine food web, as evidenced by presence of dense mats of green algae (*Cladophora*) and large biomasses of inverte brates (*Gammarus*) and fish (Stanford and Ward, 1986c; Blinn and Cole, this volume).

Controversy persists concerning the effects that Lake Powell and other Colorado River storage projects have on salinity. Paulson and Baker (1983a,b) suggest that reservoir operations can control salinity; Messer et al. (1983) and Edinger et al. (1984) report that the reservoirs have little or no effect (see above). We note that the error terms on the mass balance estimates are often higher than the estimated TDS retention (in excess of bank storage). The issue may be academic except for the fact that salinity at Lee's Ferry is indeed declining (Figure 5-5). Is the decline due to salinity control measures in the headwaters, salinity losses in the reservoirs, or more mesic conditions in the last decade? The question is relevant because considerable money continues to be spent on salinity control projects in the Colorado River basin (Bureau of Reclamation, 1987) when the predominant ions contributing salinity are sulfate and bicarbonate salts that have little effect on agricultural or potable uses. Indeed, sulfate constitutes one-half of the TDS in the Colorado River (Paulson and Baker, 1983b). Mancos and other shale formations, which are widespread on the Colorado plateau (Schumm and Gregory, 1986), are the sources of most of the water, sediments, and salts entering Lake Powell. Harmful NaC1 is localized in the Paradox Valley and Glenwood and Dotsero springs areas in the headwater reaches (Paulson and Baker, 1983b). Resolution of the salinity question probably requires continued monitoring of conditions in the rivers above and below Lake Powell.

Retention of >80% of the riverine nutrient load in Lake Powell has greatly decreased the fertility and bioproduction of Lake Mead; shad-striped bass fisheries have also declined, and reduced fertility has been inferred as the cause (Paulson and Baker, 1981; Stanford and Ward, 1986c). However, we note that a similar destabilization of the food web occurred in Lake Powell with little or no change in overall trophic status. Moreover, Lake Powell is oligotrophic despite the fact that the reservoir sequesters the riverine solids load. Attempts to artificially fertilize Lake Mead to increase bioproduction and recover the fishery did not provide sustained results; rather, the artificial fertility pulses quickly attenuated and also desynchronized cohorts of predator and prey species (as described above). These observations support the idea that the producer components of lacustrine food webs are not affected much by cyclic or transient changes in the higher consumer populations (i.e., trophic status and food webs generally are controlled bottom up by nutrient supply). We suggest that greater attention be given to cohort-specific growth patterns and the effects of angler harvest in an attempt to better explain shad-bass dynamics in Lake Powell and Lake Mead. However, it is clear that the presence of Lake Powell has vastly altered the chemistry and bioproduction of both the Colorado River and Lake Mead.

Paulson (1983) also showed that cold water from Lake Powell has reduced the net heat budget of Lake Mead, causing less evaporation and an average salinity decrease of at least 9 mg/liter, and suggested that salinity control would be enhanced if water were discharged from the surface rather than the hypolimnion of Lake Mead. This would also retain nutrients and perhaps stimulate productivity, in turn which would encourage calcite precipitation, providing a secondary control mechanism.

Clearly, management of water quality or fisheries must take into account the effects of upstream regulation and management actions in addition to reservoir-specific considerations.

Stream Regulation and the Manifestation of Serial Discontinuity

Production of algae, mainly *Cladophora glomerata*, is maintained by conditions of constancy (i.e., transparent summer-cool, winter-warm waters, stable substratum, and nutrient regime) in the tailwaters. Large populations of invertebrates, especially amphipods (*Gammarus lacustris*) support a very productive trout fishery. Similar biogeochemistry exists in headwater segments upstream. Thus, Lake Powell resets river conditions to reflect habitats that exist 400+ km upstream (two to three stream orders). This discontinuity (sensu Ward and Stanford, 1983) is gradually ameliorated in the Grand Canyon segment and then reset again by Lake Mead (Stanford and Ward, 1986b).

AN ECOSYSTEM APPROACH TO MANAGEMENT

The limnology of Lake Powell is influenced by hydrodynamics of the rivers that fill the reservoir. Moreover, the hydrodynamics of the reservoir, as related to use of the dam to store flood waters and generate hydropower, control the biophysiology of the Colorado River downstream from Lake Powell through the Grand Canyon. The limnology of Lake Mead is also coupled to Lake Powell. Thus, it seems reasonable to expand the idea of the Glen Canyon area as an ecosystem (Marzolf et al., 1987) to include the tributaries of Lake Powell, the reservoir itself, the Colorado River from Glen Canyon Dam to Lake Mead, and Lake Mead. However, even bounding the ecosystem in this manner is probably flawed, since the limnology of the upper basin has a major influence on the quality and quantity of water reaching Lake Powell and effluents from Lake Mead clearly influence downstream environments. We conclude that (1) an ecosystem perspective is requisite because of the biophysical connectivity of the reservoir and rivers and (2) the ecosystem boundaries must be determined by the nature of the management or scientific question.

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6

Algal and Invertebrate Biota in the Colorado River: Comparison of Pre- and Post-Dam Conditions

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INTRODUCTION

This paper reports present knowledge of the algal and invertebrate communities in the Colorado River between Glen Canyon Dam and Lake Mead. Both preimpoundment and postimpoundment conditions are discussed, including recent studies on the proposed changes of regulated flow on algal and macroinvertebrates in the Colorado River. Case studies in other lotic ecosystems with regulated flow that are germane to the algal and macroinvertebrate communities in the Colorado River are also reviewed. Recommendations for future studies and management operations are provided.

PREIMPOUNDMENT CONDITIONS

Algal Communities

There are few published reports on the physicochemical conditions of the preimpounded Colorado River that relate to the growth and development of algal communities. Woodbury et al. (1959) reported that the stretch of river through Glen Canyon contained high sediment loads during the periodic torrential flows of winter (>2,832 m^3 s^{-1}), but was nearly clear during the low flows (113 m^3 s^{-1}) of late summer. The average suspended sediment load in the lower Colorado River before impoundment was 3.5 times higher than after the construction of Glen Canyon Dam (Dolan et al., 1974; Stanford and Ward, 1986; Stanford and Ward, this volume). Substratum available for algal attachment included (1) scoured rock faces in areas of rapids and cataracts and (2) fine sediment in backwaters and along the inner side of river bends. (Woodbury et al., 1959) reported no data on the levels of algal nutrients (nitrogen, phosphorus, and silica).

Flowers (1959) reported 53 taxa of riverine algae, including 28 chlorophytes and 20 diatom taxa, in selected tributaries of Glen Canyon. *Spirogyra, Zygnema* and *Cladophora* were the dominant filamentous chlorophytes in these collections. He did not include quantitative estimates of algae, nor did he provide a list of algal species restricted to the mainstream.

Williams and Scott (1962) presented seasonal quantitative data on the diatom taxa from a site near Page, Arizona, and Williams (1964) reported densities (400–1600 cells ml^{-1}) of the dominant diatom taxa, *Diatoma vulgare* Bory, *Gomphonema olivaceum* (Lyngb.) Kütz., *Navicula viridula* (Kütz.) Kütz., Synedra ulna (Nitz.) Ehr., and two species of *Surirella* at several sites along the Colorado River below Cataract Canyon. Weber (1971) reported similar results at a water pollution surveillance station near Page, Arizona.

Aquatic Invertebrates

An accurate appraisal of the changes that have occurred in the composition of the aquatic invertebrates in the Colorado River since Glen Canyon Dam was closed is difficult because of the limited literature on preimpoundment fauna and the introduction of exotic species from other parts of the continent. Prior to 1963, studies were concerned with species living in tributaries or nearby springs; the main channel was neglected (Pilsbry and Ferriss, 1911; Moore and Hungerford, 1922; Gregory and Moore, 1931; Searl 1931a,b; Woodbury et al., 1959). Musser (1959) listed aquatic insects from the Colorado River in Glen Canyon and from some of the tributaries. Although not concerned with the reaches of the river below the dam, his data are the best comparable material on insects that we have.

There are published accounts of events in other western canyons that permit some generalizations. Of these, the published data from research in Green River, Utah may be especially important. The Green River is the largest tributary entering the Colorado River, and information collected before and after the closing of Flaming Gorge Dam is especially applicable to the events that have occurred in the Colorado River below Glen Canyon Dam (Pearson, 1967).

POSTIMPOUNDMENT CONDITIONS

Algal Communities

Several algal surveys have been conducted in the Colorado River since the closure of Glen Canyon Dam in 1963. Sommerfeld et al. (1976) and

Crayton and Sommerfeld (1978, 1981) reported 127 species of sestonic phytoplankton in the Colorado River and concluded that many of the planktonic species were attached forms that had been dislodged due to widely fluctuating river levels and high current velocity. Nearly 58% of the phytoplankton community was composed of diatoms, and the dominant species were *Diatoma vulgare, Rhoicosphenia curvata* (Kütz.) Grun., and *Cocconeis pediculus* Ehr. Many of the phytoplankters apparently originated from Lake Powell. For example, of the 20 dominant algal species listed for Warm Creek Bay, Lake Powell (Stewart and Blinn, 1976; Czarnecki and Blinn, 1977), eight species were found to be common to both river and lake. Crayton and Sommerfeld (1978) reported that cell densities for diatom species in the Colorado River after impoundment were over 1,600-fold lower than cell densities prior to the impoundment of the river (Williams, 1964). Crayton and Sommerfeld (1979) also reported on the composition and abundance of phytoplankton in the tributaries of the lower Colorado River.

Cladophora glomerata (L.) Kütz. is presently the dominant, attached filamentous green alga in the Canyon system, especially between Glen Canyon Dam and the Paria River, and at the mouths of major tributaries (Usher et al., 1986). The alga is also common in sestonic stream drift in the Colorado River during high flows (Haury, 1981; Leibfried and Blinn, 1986). Recently, Usher and Blinn (1990) estimated the average biomass of *C. glomerata* for sites at and above Lee's Ferry to be 144 g m^{-2} (standard error [SE] ± 4.1), compared with 17.2 g m^{-2} (SE ± 5.5) at the mouths of selected tributaries below Lee's Ferry. The relatively high biomasses of *C. glomerata* in the upstream tailwater sites may result from the abundance of stable rock surfaces for attachment and the clear, nutrient enriched waters from the hypolimnial releases of Glen Canyon Dam (Stanford and Ward, 1986). The rather abrupt decrease in standing crop of *C. glomerata* below Lee's Ferry most probably resulted from the periodic inputs of suspended sediment (limited light penetration) from major tributaries such as the Paria River and the Little Colorado River (Cole and Kubly, 1976).

Cladophora growth was frequently reduced or absent on the upstream side of boulders at Nankoweap (river km 84) because of the intense sandblasting by suspended sediment (D. W. Blinn, personal observation). Furthermore, the limited growth that did occur on the sand-impacted upstream faces frequently formed condensed mosslike tufts rather than the highly branched growth form on the more stable rock substrates.

Usher et al. (1986) reported a progressive increase in biomass of *C. glomerata* with increased channel depth at sites above Lee's Ferry but an overall decrease in biomass with depth at a site below Lee's Ferry (Nankoweap, 84.5 km). The decrease in *Cladophora* biomass with increased channel depth at the lower site may have resulted from the rapid attenuation of light due to periodic high sediment loads.

C. glomerata is an important biotic component in the overall structure of the Colorado River ecosystem, especially in the tailwaters (25 km) below Glen Canyon Dam, and therefore warrants further study. This filamentous green alga serves as a substratum for invertebrates and refuge from fish predators and fast-moving water. Leibfried and Blinn (1986) found a significant positive relationship between the standing crops of *C. glomerata* and *Gammarus lacustris* Sars at Lee's Ferry during the months of July and October 1985. Other investigations also have reported a close association between *Cladophora* and invertebrates in other lotic ecosystems (Blum, 1957; Whitton, 1970; Neel, 1963).

The highly branched filaments of *C. glomerata* also provide enormous surface areas for the attachment of epiphytic diatoms which are used as food by aquatic invertebrates (Blinn et al., 1986) and perhaps indirectly or directly by fish (Montgomery et al., 1986). On the other hand, dense stands of attached filamentous algae interfere with anglers (Whitton, 1970) and may interfere with spawning grounds of fishes, especially salmonids (Skulburg, 1984).

Czarnecki et al. (1976) reported 345 taxa of periphytic algae (attached algae) in the seeps, the mouths of tributaries, and the Colorado River in the Grand Canyon. Greatest abundance of periphytic algae was recorded during the summer (June–July). Of the taxa reported, 65% were diatoms, 24% were cyanobacteria, and 10% were chlorophytes. A red alga, *Batrachospermum* sp., was reported at the confluence of Diamond Creek (river km 362). Recently another red alga, *Audouinella* , appeared in the mainstream (personal observation, 1984). *Audouinella* is frequently attached to the filaments of the green alga, *C. glomerata* , and is most commonly found in the deeper sections of the river channel above the confluence of the Paria River. The appearance of *Audouinella* in the Colorado River is not unexpected, since most freshwater rhodophytes are confined to rivers and streams and species of *Audouinella* can tolerate flows exceeding 5m s^{-1} (Sheath, 1984).

Czarnecki and Blinn (1978) reported 235 diatom taxa from the Colorado River and tributaries and from springs in the Glen and Grand Canyon systems. The dominant taxa were *Diatoma vulgare, Synedra ulna*, and *Cocconeis pediculus*. The two former species were reported to be common within the river system prior to the impoundment of Lake Powell (Flowers, 1959), but *C. pediculus* appears to have increased in relative importance since the time of impoundment. This may be a function of the frequent epiphytic association of *C. pediculus* on *C. glomerata* (Stevenson and Stoermer, 1982; Blinn et al., 1989a) and perhaps indirectly implies that the biomass of *Cladophora* has increased since the closure of Glen Canyon Dam.

Usher et al. (1986) quantified the epiphytic diatoms associated with *Cladophora* at two sites above Lee's Ferry and at the confluences of four major tributaries below Lee's Ferry. *Achnanthes affinis* Grun., *Cocconeis pediculus, Diatoma* *vulgare*, and *Rhoicosphenia curvata* made up over 80% of the diatom composition at sites above Lee's Ferry, while these four taxa were significantly less important at the downstream sites. *Gomphonema olivaceum, Cymbella affinis* KHtz., and *Nitzschia dissipata* (KHtz.) Grun. became progressively more important at downstream sites. The explanation for this change in species composition is not yet known, but the relatively high tolerance to suspended sediment by the latter three diatom species may be a factor (Lowe, 1974; Bahls et al., 1984). There was also a fourfold decrease in densities of epiphytic diatom populations at sites below Lee's Ferry compared with sites above Lee's Ferry, and there was a significant decrease in cell density with increasing channel depth. Both patterns may relate to the relationships between suspended sediment, water depth, and light and nutrient attenuation.

In other studies of epilithic diatoms, Carothers and Minckley (1981) listed total numbers of taxa for eight major tributaries to the Grand Canyon system, and Usher et al. (1984) listed the periphytic diatom taxa in Bright Angel, Garden and Pipe creeks in the canyon system. The periphytic diatom communities were quite distinct from the diatom community associated with *Cladophora* in the main stream.

AQUATIC INVERTEBRATE COMMUNITIES

Records of Intentional Stocking

Even if studies had been made on the aquatic invertebrates of the Colorado River before the dam was closed, the intentional introduction of exotic species after 1963 (Stone and Rathbun, 1968, 1969) would have prevented accurate comparisons. Some events occurring between April and the end of July 1967 underscore this. Ten thousand immature ephemeropterans secured from a commercial source in Minnesota were planted in three sites between the dam and Lee's Ferry. Shortly afterward, 10,000 snails (*Physa* and *Stagnicola*), 5000 leeches, and thousands of insects representing at least 10 families from the San Juan River in New Mexico were planted. Finally 2000 crayfish collected from the Little Colorado River near Springerville were introduced (Stone and Queenan, 1967).

Zooplankton

From Haury's (1986, 1988) analyses, it appears that zooplankters of the Colorado River below Glen Canyon Dam are derived from lentic populations in Lake Powell, i.e, similar to phytoplankton. Haury focused on the planktonic crustaceans and proposed that occasional surface releases from spillways would enhance the river populations and nocturnal releases would have the greatest influence. Populations of *Gammarus* would not be in creased by such manipulations, but cladoceran and copepod numbers would rise temporarily. There is good evidence that reproduction of zooplankton occurs in the river because microcrustaceans below the dam increase to at least the mouth of Diamond Creek, about 388 km below Glen Canyon Dam. Haury did note, however, that the percentage of copepod plankters in "poor condition" increased downstream.

The earlier report of Cole and Kubly (1976) included, in addition to the nonplanktonic *Gammarus*, only 4 cladocerans, 8 ostracods, and 4 copepods compared with 13, 8, and 13 listed by Haury about a decade later. Of those on Haury's list, only 16 are true plankters; the others are benthic, although they sometimes drift downstream and are sampled with the euplankters. These drifters contributed a greater biomass in Haury's samples. Cole and Kubly (1976) also listed rotifers, a collembolan, and water mites in their river collections. The last two forms are categorized best as epineustonic and, in the case of the mites, perhaps nektonic also.

One can speculate concerning the origins of some crustacean plankters in the river. During the early 1950s *Aglaodiaptomus clavipes* Schacht and *Leptodiaptomus siciloides* Lillj. were collected from Lake Mead (Wilson, 1955). Since then, *Skistodiaptomus reighardi* Marsh has been found in the lake (Paulson et al., 1980) and was included in Haury's list. *A. clavipes* is a versatile western species, found in many Arizona habitats from turbid stock tanks to large impoundments; it occurs with *L. siciloides* in the impoundments on the Salt River (Cole, 1961). *L. siciloides* is widespread throughout most of the continent, as are most of the cyclopoid crustaceans reported by Cole and Kubly (1976) and Haury (1988). Distribution records suggest that *Skistodiaptomus pallidus* Herrick, the only calanoid reported by Cole and Kubly, has moved westward from the Mississippi Valley. *Skistodiaptomus reighardi, Skistodiaptomus ashlandi* Marsh, and *Leptodiaptomus* Forbes have extended their ranges southward.

The richness of faunas of backwaters along the borders of the river channel and at the mouths of tributaries should be noted, and care should be taken to preserve these refugia. Stanford and Ward (1986) noted that the much higher productivity of backwaters probably make them very important as a native fish habitat. A comparative study of the zooplankters in backwaters and in the main stream of the Colorado River during 1987–1989 revealed mean densities per cubic meter almost four times greater in the former (D. M. Kubly, personal communication). The relative increase in cladocerans was especially noteworthy. Kubly found approximately 14 times as many in quiet backwaters. By contrast, Haury (1981) found that the numbers of *Daphnia* in the terminal pools at the mouth of Kanab Creek and National Canyon were remarkably reduced compared with populations in the adjacent mainstream. He noted, however, that the cladocerans were all small, suggesting that fish had been selectively preying on the larger indi viduals. The value of cladocerans as a food supply for larval fish is especially important, for they are more vulnerable to attack than are copepod plankters.

Macroinvertebrates

The macroinvertebrates occurring in the Colorado River consist of but a few species even though there have been numerous introductions of invertebrates as discussed previously. Over the years investigators have recorded those species found in drift samples, fish stomachs, and material dredged from the riverbed. The papers of Stevens (1976) and Leibfried and Blinn (1986) and subsequent observations by Stevens (1990, personal communication) seem to apply to present conditions. The faunal list includes species of planarild flatworm, perhaps three species of the Oligochaeta, gastropod molluscs of which *Physa* predominates, a clam possibly belonging to the Sphaeriidae, the amphipod crustacean *Gammarus lacustris*, and members of six insect families. A baetid mayfly (*Baetis* sp.) has been overlooked by many observers, but it has been reported in other river systems in the tailwaters below dams (Pearson, 1967), and it appears to be increasing in the Colorado River (Stevens 1990, personal communication). Corixid bugs, a hydrophilid beetle, and at least 10 species of dipterans complete the list. Of the flies, the larvae of simuliids (at least three species), about six species of chironomids, and a ceratopogonid appear in collections.

The analyses of Polhemus and Polhemus (1976) of 14 species representing nine families of aquatic heteropterans in the Grand Canyon are instructive. Most of their collections were made in tributiaries entering about 363 km of the river below Lee's Ferry. They considered the fauna typical of the south-western United States and western Mexico. In that order of insects at least, there is no evidence of species introduced from distant parts of the continent.

Many other authors have detailed the diversity of benthic macroinvertebrates in the tributaries and their mouths in comparison with the river populations. Hofknecht's (1981) list of 52 insect families represented in 30 tributaries and springs, compared with only 5 in the main river, is typical. Carothers and Minckley (1981) presented many comparisons of biomass and density of aquatic invertebrates at the confluence of 15 tributaries and the river versus similar data from 200 m upstream in each tributary. Their data underscore once more the importance of these backwater pools; in all seasons there were marked decreases in the upper station.

Usher et al. (1984) found 42 taxa of insects and one taxon each from Gastropoda, Pelecypoda, Oligochaeta, and Arachnida in the habitats of Roaring Springs, Bright Angel, Garden and Pipe creeks of the canyon system. It is noteworthy that the caddisfly larvae (*Oligopheboides* sp.) was recently collected from Bright Angel Creek and Roaring Springs. These are the first records for this genus in Arizona (M. W. Sanderson, personal communication). The known seven species of *Oligophiebodes* are all nearctic and are confined to mountainous regions of the western United States (Wiggins, 1977), and therefore it is very surprising to find representatives of this group in the Grand Canyon. In addition, Musgrave (1935) reported the coleopteran *Helichus triangularis* from Garden Creek and is the only known record of this species north of the Huachuca and Chiricahua Mountains of southwestern Arizona.

Kondolf et al. (1989) predicted progressive armoring of the river bottom with cobbles above Lee's Ferry, which may eventually cause destruction of trout spawning areas because no gravel sources exist upstream. Whereas, the relict gravel from preimpoundment years is being washed away, the more stable substratum provides good simuliid habitat. Larvae of the simuliid flies are an important food item for fish and fisheries may benefit from increased blackfly populations. Larval chironomids, by contrast, are found in silty areas or in *Cladophora* beds.

Simuliid and chironomid dipterans that metamorphose from aquatic larvae to flying adults are involved in both the aquatic and terrestrial food webs in the Grand Canyon (Stevens and Waring, 1988). This is natural and has little or nothing to do with flow regulation. More unusual is the phenomenon of *Gammarus* stranded in pools along the stream banks falling prey to lizards (personal observation).

The Amphipod Gammarus Lacustris

One of the most important items in the diet of the Colorado River exotic and native fishes is the amphipod crustacean *Gammarus lacustris* . This species is incorrectly termed freshwater shrimp in many publications, whereas "scud" is more appropriate. Details are lacking about its history in the river, although it began in December 1932 when 50,000 individuals were planted in the "moss" of Bright Angel Creek (Anonymous, no date). Scuds do currently occur in Bright Angel Creek, and other tributaries entering the river below Glen Canyon Dam. In 1965 more scuds were introduced at Lee's Ferry and in the spring of 1968 many more were planted near the diversion tunnels below the dam (Stone and Rathbun, 1969). The source or sources of these introduced amphipods was not reported. Titcomb (1927) pointed out that millions of *Gammarus limnaeus* (an older name for *G. lacustris*) from a commercial source in Caledonia, New York (about 20 km south of Rochester), had been distributed for stocking trout waters in various parts of the country more than six decades ago. The natural distribution of this crustacean probably has been blurred by human activities.

G. lacustris is widespread in northern Asia and Europe. It occurs in most of Alaska and Canada, perhaps being the only freshwater species of *Gammarus* that reached North America via past Bering Sea land bridges. Local southern populations are found in California, Nevada, Arizona, and New Mexico. It is a cold-stenothermous form, not thriving in warm waters with low pH and low salinity.

Exotic and Unusual Species

In addition to the existence of northern and eastern crustaceans in the Colorado River plankton populations, we can expect the arrival of certain cosmopolitan species. Artificial waters seem to serve as stepping stones for exotic species as they spread geographically. The appearance of the medusa *Craspedacusta sowerbyi* Lankester in Lake Mead (Deacon and Haskell, 1963) and in the small impoundment of Lake Patagonia in southern Arizona (Kynard and Tash, 1974) is typical. It could be expected in Lake Powell and hence the Colorado River below the dam.

The unusual tubificid worm *Branchiura sowerbyi* Bedd. has appeared in canals in Tempe, Arizona and in Saguaro Lake, an impoundment on the Salt River about 40 km northeast (Cole, 1966). One could predict future invasion of this cosmopolitan worm into Lake Powell. Furthermore, the Asiatic clam *Corbicula* sp. has appeared in other Arizona impoundments, canals, and streams. Some references to sphaeriid clams in the Colorado River below Glen Canyon Dam may be referable to *Corbicula* from a different pelecypod family.

Carothers and Minckley (1981) discussed the apparent establishment of the exotic parasite *Lernaea cyprinacea* Linn. In some tributaries, they found this parasitic copepod attached to native fishes, and its numbers may be increasing. It thrives best in still waters of fish hatcheries, ponds, and lakes but has been known for many years in the Arizona Salt, Verde, and Gila River drainage systems, where it parasitizes at least three species of native fishes (James, 1968). It probably arrived in Arizona in the late 1800s or early 1900s. Also, it has been reported from the Jordan River, Utah, where it attacks *Gila atraria* (Bradford and Grundmann, 1968). The slow flow of the Colorado River may not inhibit its increase, and this worldwide species, perhaps originally from Asia, may become a threat if a strain resistant to cold water develops. It is presently increasing in the tributaries (Carothers and Minckley, 1981).

MODIFICATIONS IN BIOTA DUE TO REGULATED FLOWS

Colorado River Studies Between Glen Canyon and Lake Mead

Stranding of plant and animal communities during sudden low-flow periods in regulated rivers may be very important in structuring biotic commu nities. Usher and Blinn (1990) experimentally tested the influence of short term stranding (exposure to air) on the biomass and chlorophyll *a* of *Cladophora glomerata* in a simulated stream environment. Their study indicated that exposures of 12 daylight hours or longer resulted in significant reductions in *C. glomerata* biomass, and exposures of 1 d or longer decreased chlorophyll *a* concentrations per gram dry weight of *Cladophora* biomass by over 50% from submerged control treatments. There were no significant differences in biomass between control treatments and treatments exposed to the atmosphere for 12 hours of darkness, perhaps suggesting lower desiccation rates during the night. *C. glomerata* treatments subjected to 12- and 24-hour exposure-submergence cycles for a 2-week period showed over a 45% decrease in *Cladophora* biomass from control treatments.

Cladophora is frequently an important component of seston drift in the Colorado River (Haury, 1981; Leibfried and Blinn, 1986). Periodic, short-term exposures (12 to 24 hours) of river substratum during low flows may, increase drift of *Cladophora* in the Colorado River. It seems logical that if holdfast systems of plants are dried during extended periods of stranding they would become weaken and detach, and would enter the water column as drift during re-wetting (Usher and Blinn 1990). In addition, the increased three-dimensional development of algal populations due to growth would increase the natural shearing effect by current and contribute to detachment (Vogel 1981). However, Leibfried and Blinn (1986) found no significant differences in *Cladophora* drift rates in the Colorado River at Lee's Ferry between months with relative steady flows (May–September 1985; flows fluctuated <8,000 cfs) and fluctuating flow periods (October–December 1985; flows fluctuated >20,000 cfs). It is noteworthy that stranding periods were <12 hrs during months of regulated flow.

Leibfried and Blinn (1986) did find a significant increase in stream drift of *Gammarus* during the rising arm of discharges following low flow periods (<5,000 cfs). *Gammarus* increased from 10.7 animals per hour for months with relatively steady flows to 42.3 animals per hour for months with more fluctuating flows. They observed that *Gammarus* left the stranded *Cladaphora* filaments during low flows and moved into shallow pools of water. When flows increased the amphipods were swept downstream into the water column. Further studies on exposure and on the importance of regulated flow and discharge rates for detachment and drift are essential to help clarify the importance of these disturbances on the biotic communities in the Colorado River.

Cladophora glomerat does display a few adaptations to reduce the impact of widely fluctuating flow regimens caused by dams. Recently, Usher (1987) reviewed the literature on the physicochemical requirements of *Cladophora*, and Usher and Blinn (1990) discussed the importance of the general plant body design of *Cladophora* to help reduce the effects of exposure. Typically, the longer, outer filaments of *Cladophora* collapse on themselves and trap water like a sponge as the water level recedes in regulated rivers. This process tends to protect the innermost filaments from high light and reduce desiccation rates. In addition, the dense assemblages of epiphytic diatoms with their mucilaginous secretions may further help to slow desiccation rates in *Cladophora* during periods of short-term stranding in regulated rivers. These adaptations may, in part, explain why *Cladophora* populations are commonly associated with marine intertidal communities and perhaps preadapted to tolerate fluctuating flow regimes in rivers.

Diatoms are a common, if not the dominant, attached algal component in many lotic ecosystems (Whitton, 1975; Lowe, 1979), including streams in southwestern United States (Blinn et al., 1981; Duncan and Blinn, 1989a). The Colorado River ecosystem is no exception (Czarnecki and Blinn, 1977, 1978). These microalgae provide food for invertebrates and fish as well as oxygen for general community metabolism.

The U.S. Fish and Wildlife Service has suggested a modification in the water release program at Glen Canyon Dam in order to improve the habitat for the humpback chub (*Gila cypha*). The new plan proposes to release warmer subsurface water (>18°C) from the epilimnion of Lake Powell instead of the present, cool water (10–12°C) released from the hypolimnion of the reservoir (Maddux et al., 1987). Recently, Blinn et al. (1989a) examined the importance of elevated water temperature on the community structure of periphytic diatoms in the tailwaters (25 km below Glen Canyon Dam) of the Colorado River. They found that the relative frequencies of the numerically important larger upright species such as *Rhoicosphenia curvata* and *Diatoma vulgare* decreased when water temperature was elevated to 18°C or higher. In contrast, the relative abundance of the smaller and closely adnate cells of *Cocconeis pediculus* increased with elevated water temperatures. This compositional shift in epiphytic diatoms as a result of elevated water temperature may be potentially important to the aquatic food chain in the Colorado River because recent studies have demonstrated that larger upright diatom species are commonly consumed by macroinvertebrate grazers in preference to smaller adnate diatom taxa (Sumner and McIntire, 1982; Steinman et al., 1987; Colletti et al., 1987; Blinn et al., 1989b). Furthermore, Blinn et al. (1986) reported that the diet of *Gammarus lacustris*, an important invertebrate grazer in the tailwaters of Glen Canyon Dam, consisted primarily of upright taxa (*D. vulgare* and *R. curvata*) and rarely of the closely adnate species, *C. pediculus* . Montgomery et al. (1986) and Leibfried (1988) have also suggested the importance of epiphytic diatoms as a food resource for rainbow trout in the Colorado River.

Peterson (1987) studied the importance of desiccation on the structure of diatom communities in the tailwaters of Lake Mead in the Colorado River. He reported that biomass and density were reduced by desiccation on sheltered substrata, as a function of regulated flow.

STUDIES ON OTHER REGULATED RIVERS

Over the past several decades, authors have reviewed the various ways that manmade reservoirs frequently modify downstream environments (Neel, 1963; Ward, 1974, 1975, 1976; Baxter, 1977; Ward and Stanford, 1979; Obeng, 1981; Lillehammer and Saltveit, 1984; Petts, 1984; Craig and Kemper, 1987). The general consensus is that regulated rivers subject biological communities to the following downstream conditions: (1) reductions in seasonal flow variability, (2) alterations in the timing of extreme flow events, (3) unnatural pulses in flow during periods of peak power demands, (4) clarification of water, (5) diel and seasonal constancy of water temperatures, (6) a significant increase in armored substrates, (7) modifications in nutrient regimes, and (8) the appearance of lentic plankton beneath reservoirs. Ward and Stanford (1987) also suggest that reservoirs reduce mean annual runoff because of high evaporation rates in reservoirs, which in turn can increase salinity. It is noteworthy that the position of a dam along the river continuum (Vannote et al., 1980) is instrumental in the magnitude of these downstream modifications (Ward and Stanford, 1983).

Plant Communities

Typically, the conditions of regulated flow described above increase the standing crops of both attached algae and aquatic macrophytes, as well as aquatic mosses (Neel, 1963; Lowe, 1979). Ward (1976) reported 3–20 times more epilithic algae in regulated portions of the South Platte River below Cheesman Reservoir, Colorado, than in unregulated channels. Likewise, workers have reported substantial increases in algal biomasses below other reservoirs in Colorado (Zimmerman and Ward, 1984; Dufford et al., 1985) and in Utah (McConnell and Sigler, 1959), Montana (Gore, 1977), Great Britain (Petts and Greenwood, 1981), Norway (Skulburg, 1984), and Australia (King and Tyler, 1982). These observations concur with reports by Usher and Blinn (1990) in regard to the high algal biomass in the tailwaters (28 km) of the Colorado River below Glen Canyon Dam. It is noteworthy that Ross and Rushforth (1980) did not find significant differences in diatom communities above and below a newly formed reservoir on Huntington Creek, Utah. In addition, Walker (1979) reported low algal and macrophytic development in the Murray River, Australia. He suggested that the potential effects of nutrient enrichment and regulated flows, which normally enhance plant development, are greatly overridden by the prevailing high turbidity in the lower Murray River.

Commonly, filamentous green algae, especially *Cladophora glomerala* , and in some instances *Microspora amoena* (Kütz.) Rabh. (Skulburg, 1984) and *Ulothrix zonata* (Weber and Mohr) Kütz. (Rader and Ward, 1988), and the chrysophyte *Hydrurus foetidus* (Vill.) Trev. (Ward, 1976; Skulburg, 1984) dominate the attached macroalgal communities below reservoirs. The development of *C. glomerata* implies nutrient enrichment and high water turbulence (Whitton, 1970, 1975; Usher, 1988), while *U. zonata* and *H. foetidus* are considered coldwater rheobionts (Blum, 1960); all of these environmental conditions occur in the tailwaters of hypolimnion-released reservoirs. Regulated streams tend to favor extensive developments of diatom species that are typically coldwater stenotherms and rheobionts (Lowe, 1979; Blum, 1960). Epiphytic diatoms from the genera *Achnanthes, Cocconeis, Cymbella, Diatoms, Diatomella* , and *Synedra* and frequently associated with regulated streams (Lowe, 1979; Petts, 1984; Dufford et al., 1987). It is noteworthy that *Diatoms vulgare* is one of the more common diatom taxa associated with regulated streams, including the tailwaters of Glen Canyon Dam, and is frequently epiphytic on *Cladophora* and prefers cool, flowing water with high nutrients (Lowe, 1979). All of these conditions commonly prevail in the tailwaters of reservoirs.

The environmental conditions most frequently cited for the enhancement of algal growth below dams include (1) high clarity of water due to the truncation effect of reservoirs on the downstream transport of sediment, (2) postponement or absence of freezing conditions as a result of the diel and seasonal constancy of water temperature, (3) increased stability and availability of armored substrates for attachment, (4) absence of sudden spates and droughts, and (5) increased nutrient availability. Spence and Hynes (1971) also suggest that the constant cool waters below reservoirs reduce the number of algal grazers.

The importance of nutrient enrichment below reservoirs on algal growth has been reviewed by several investigators (Lowe, 1979; Hannan, 1979; Skulburg, 1984; Petts, 1984; Ward and Stanford, 1987). The nutrients considered to be most influential on algal populations below reservoirs include phosphorus, nitrogen, and silica, but the roles of other nutrients need to be examined. For example, Patrick et al. (1969) suggested the potential importance of trace elements on the composition of lotic algal communities.

Marcus (1980) reported that ammonia-nitrogen was the only stream physico-chemical parameter that correlated with increased periphytic chlorophyll *a*. Other factors normally considered important in causing variations in algal growth in regulated rivers (i.e., water temperature, flow rate, and streambed characteristics) apparently had only a secondary influence on algal growth because these conditions were similar at all sites. Hannan and Young (1974) also reported an increase in ammonia-nitrogen below a reservoir on the Guadalupe River in Texas, while Armitage (1984) reported that nitrogen levels in coarse particulate seston were higher in regulated sections of streams. The mobilization of nitrogen may result from mineralization and nitrogen fixation in upstream reservoirs (Rada and Wright, 1979). Armitage (1984) concluded that increases in plant growth as a result of nutrient inputs from reservoirs alter the character of substrates for zoobenthos by the increasing surface area available for colonization and increasing retention of particulate material through the filtering action of plants. Hannan (1979) and Walker (1979) discussed the potential for reduced dissolved oxygen concentrations in the hypolimnetic waters of reservoirs, while Ward and Stanford (1987) suggested the importance of reduced compounds such as H2S of tailwater biotic communities, especially below eutrophic reservoirs during late summer.

Periodic spates are important in regulating the abundance and structure of algal communities in lotic environments (Fisher et al., 1982). Although current velocity is an important variable because the rapid exchange of water around cell surfaces removes wastes and replenishes nutrients (Whitford and Schumacher, 1961, 1964), extreme discharges can dislodge attached algal communities and severely reduce standing crop (Fisher et al., 1982; Skulburg, 1984; Power and Stewart, 1987; Duncan and Blinn, 1989). It is likely that the Colorado River did not develop extensive algal populations prior to the closure of Glen Canyon Dam because of periodic scouring by turbid flood waters (Woodbury et al., 1959). Glen Canyon Dam has buffered these spates and allowed *Cladophora glomerata* to proliferate in the tailwaters (28 km below Glen Canyon Dam). However, the present relatively high discharges from Glen Canyon Dam may be responsible for the frequent occurrence of *Cladophora* in the drift (Haury, 1981; Leibfried and Blinn, 1986). In fact, Mullan et al. (1976) suggested that the extensive *Cladophora* populations that developed within 6 years of the closure of Glen Canyon Dam had been reduced substantially since that time as a result of the scouring action of daily discharge fluctuations of up to 140 $m^3 s^{-1}$. Aquatic macrophytes, including mosses, also show substantial increases in biomass below reservoirs (Lowe, 1979). Commonly, lotic environments show only limited development for aquatic macrophytes as a result of the frequency of turbid flood waters (Westlake, 1975; Fisher et al., 1982). However, with the stabilization of flow regimes and increased stability of substrates, a number of studies show that macrophyte standing crops increase below reservoirs (Hall and Pople, 1968; Holmes and Whitton, 1977; Haslam, 1978). Aquatic macrophytes are not important in the mainstream of the Colorado River, perhaps because of its deep channel and the magnitude of discharge below Glen Canyon Dam.

Invertebrate Communities

The most common effect of impounded rivers on the macroinvertebrate community is reduced species diversity accompanied by high density and biomass (Pearson, 1967; Pearson et al., 1968; Spence and Hynes, 1971; Fisher and LaVoy, 1972; Ward, 1976; Ward and Stanford, 1979; Zimmermann and Ward, 1984; Brusven, 1984). These findings agree with those of Leibfried and Blinn (1986) for the macroinvertebrate community in the tailwaters of Glen Canyon Dam in the Colorado River. Plecopterans (stonefly) and ephemeropterans (mayflies) are generally reduced (Ward and Stanford, 1979; Winget, 1984; Pett, 1984; Rader and Ward, 1988), while amphipod crustaceans and simuliid larvae (dipterans) are enhanced in many impounded rivers (Pfitzer, 1954; Hilsenhoff, 1971; Spence and Hynes, 1971; Ward, 1976; Ward and Stanford, 1979). The dam's effects are lessened downstream and eventually lower reaches of the stream may recall preimpoundment conditions (Voelz and Ward, 1989).

There are several factors responsible for the observed changes in community structure of macroinvertebrates below reservoirs. Ward (1976) suggested that the dense growths of algae prevent the establishment of certain forms of insects that use suckers or friction pads. The lack of smooth rock surfaces below impoundments, which are algal free, may be especially restrictive to heptageniid mayflies (Ward, 1976). Furthermore, Spence and Hynes (1971) suggested that oxygen depletion due to the high respiratory demands of dense algal stands caused the disappearance of three predatory plecopterans below the Shand Dam in Ontario, Canada.

In situations where deep hypolimnial water is released from reservoirs, macroinvertebrate communities have been adversely affected. This results from the loss of particulate organic matter in upstream reservoirs (Armitage, 1984). Larger zooplankters do not persist in downstream flows, and planktonic organisms from hypolimnion releases are not a suitable food source for filter-feeding benthic forms downstream (Ward, 1975).

Modifications in thermal conditions also contribute to the compositional changes in macroinvertebrates below reservoirs. The thermal constancy and seasonal temperature patterns below dams may disrupt thermal signals essential for the completion of life cycles for certain macroinvertebrates. For example, the annual number of degree days may not be sufficient for the completion of a life cycle (Ward, 1976; Hauer and Stanford, 1982).

On the other hand, conditions below reservoirs may enhance the development of some species. For example, *Gammarus lacustris* prefers cool to cold water conditions in the summer (Bousfield, 1958). Spence and Hynes (1971) also suggested that increases in amphipod crustaceans resulted from the increase in available microhabitats and food within the algal mats. Enhanced standing crop of certain macroinvertebrates have also been attributed to increased plankton levels (Cushing, 1963).

RECOMMENDED RESEARCH

Based on our present knowledge on the algal and invertebrate communities in the Colorado River, the following list of general recommendations is provided.

1. Further studies should be done on the seasonal abundance and distribution of *Cladophora glomerata* within the Colorado River ecosystem. We recommend that, in cooperation with the Bureau of Reclamation, collections be made under different flow regimes (i.e., typical range of regulated discharge and steady flow) at several locations in the tailwaters of Glen Canyon Dam at various depths within the river channel to establish comparative baseline information on the population dynamics of this important primary producer under regulated flow in the Colorado River ecosystem.
2. Since *Cladophora glomerata* is potentially an important biotic component in the aquatic food web of the tailwaters of Colorado River ecosystem, we recommend that threshold flow rates between optimum growth and primary production as well as loss of plants through natural shearing force be determined for the *C. glomerata* population in the Colorado River. It is likely that some optimum flow schedule could be established that would provide a level of *Cladophora* growth and maintenance that would most benefit the overall Colorado River ecosystem.
3. The importance of *Cladophora glomerata* and associated epiphytes to the Colorado River ecosystem should be established. For example one could (a) determine the importance of *C. glomerata* as a habitat and as a refuge for invertebrates from fish predators in the Colorado River ecosystem and (b) determine the importance of *C. glomerata* and associated epiphytic diatoms as food for invertebrates and selected fish species in the Colorado River ecosystem.
4. Develop a clear understanding of the food web in the tailwaters of Glen Canyon Dam compared to areas downstream in the Grand Canyon.
5. Undertake phenological studies of invertebrates in the Colorado River ecosystem, especially if temperature patterns are likely to change because of different release patterns from Glen Canyon Dam, i.e., epilimnial versus hypolimnial releases.
6. There is a need to determine the influence of different flow regimes on the detachment and drift rates of *Cladophora glomerata* and epiphytic diatoms as well as for macroinvertebrates. With the cooperation of the Bureau of Reclamation, drift rates for *Cladophora* and macroinvertebrates could be measured for various levels of water release from Glen Canyon Dam. The importance of *Cladophora* and invertebrate drift to the overall food web, especially fish populations, in the Colorado River needs clarification.
7. We should study and protect the biota of backwater refugia in major tributaries that enter the Colorado River.
8. There is a need to develop models that would determine the effects that various modifications in physicochemical parameters have on plant and animal communities in regulated rivers.

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7

Native Fishes of the Grand Canyon Region: An Obituary?

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The highly endemic fish fauna of the Colorado River downstream from Glen Canyon Dam has been largely extirpated. Damming, diversion. and other human regulation stabilized the system, which enhanced introduced nonnative fishes and proved detrimental to native species. Historical accounts are used to (1) reconstruct the ecology of fishes in a pristine Colorado River, (2) document changes resulting in the decline of native species, and (3) indict the introduction and establishment of alien fishes as the ultimate factor in extirpation of the natives. Despite legislation and dedicated efforts by scientists and fisheries managers in the 1970s and early 1980s, trends toward extinction of native fishes were not reversed. Deemphasis of environmental issues because of economic and political pressures for development in the later 1980s makes survival of this unique fauna doubtful.

INTRODUCTION

The U.S. National Park Service was founded in 1916 with a mandate to preserve resources Placed under its care "unimpaired for the enjoyment of future generations." Shortly thereafter, in 1919, Grand Canyon National Park was established to protect the natural attributes of spectaculation gorges cut by the Colorado River. These efforts failed for some of the native aquatic biota. Construction and operation of dams and reservoirs outside the park resulted in a chain reaction of environmental change that forced its native fishes to local extinction (Dolan et al., 1974; Johnson and Carothers, 1987).

This paper concerns the decline and disappearance of indigenous fishes from the lower Colorado River, including the Grand Canyon region. To document this, the fishes are first placed in the context of a pristine ecosystem, reconstructed logically and with a modicum of speculation from historic data. Demise of the fauna started just after 1900, as the river was progressively harnessed for water supply, flood control, and power production. The fish fauna collapsed from downstream to upstream, in the same sequence as the river was regulated. Reasons for this ecological catastrophe are discussed for individual species and for the fauna as a whole. Finally, the grim prognosis for native fishes is tempered by a brief review of legal statutes, scientific facts, and moral obligations, all of which exist to save them. But before this happens, it is clear that society must develop an ethic sufficient to realize this goal.

THE PRISTINE HABITAT

The Colorado River collects water, sediments, and dissolved solids from more than 600,000 km^2 of mountains, plateaus, and basins (Graf, 1985). From north to south, the river flows through the Rocky Mountain, Colorado plateau, and basin and range physiographic provinces. High elevations provide spring and early summer runoff in the form of snowmelt, and most of the water yield is from that source. Historically, low flow predominated in summer through winter, with late summer spates in the south, where a bimodal pattern of winter rains and late summer monsoons prevails.

After leaving the Rockies, the river winds through desert, where significant amounts of water are lost to evaporation. Ions are concentrated and added by inflowing salt springs; as a result, total dissolved solids increase. Along with this material are sediments from the headwaters, joined by even more stripped from the sparsely vegetated deserts and plateaus by runoff of infrequent, often violent rains.

The course of the river almost defies description. After the steep headwaters, it alternatively meanders through broad, aggraded valleys and then slices through bedrock uplifts. Most valley reaches are now modified for agriculture. The river is constrained and channelized from its original state of flowing through braided channels, over bars of shifting sand and gravel, and between alluvial banks. Runs and riffles were smooth and strong, and oxbow lakes, backwaters behind sandbars, and other lentic habitats were common. The canyons, if not used for a dam site or drowned by a reservoir, remain much the same as they were. They vary in morphology, with steep or sloping walls. Some are deeper than 1,500 m, others are less deep. A few are relatively straight, while most are sinuous. Rapids are common, with high waves, whirlpools, and other turbulence creating "whitewater" (in the jargon of the river), which reflects underwater obstructions such as bedrock dikes, stony debris from side canyons, or rockfalls from the canyon walls (Leopold, 1969; Dolan et al., 1978). Between rapids are "pools," where deep, strong currents, or flatwaters, flow through unobstructed channels.

Most accounts of the river stress its variability in discharge and sediment load. In a 40-year, pre-dam period of record, discharge at Yuma, Arizona, varied over five orders of magnitude, from 0.5 to 7,100 $m^3 s^{-1}$ (Dill, 1944). Variations in transported sediment were also substantial. On an annual basis, materials accumulated during low discharge, to again be moved by high water in spring. Longer-term cycles also existed. From 45.4 to 455 million metric tons $year^{-1}$ of silt was transported through Grand Canyon between 1922 and 1935 (Howard, 1947; Howard and Dolan, 1981), while records at Yuma varied from 36.3 to 326 million metric tons in the same period. Thus, a significant percentage was aggrading on the floodplain and along the channel. Bedload must have varied similarly, but measurements then, as now, were unreliable. Degradation of these deposits ocurred during episodic realignment and cutting of valley deposits by major floods, when virtual slurries of sand, gravel, and boulders must have ground inexorably through canyons. Such processes are graphically described in pre-dam accounts of building and slouching of banks and bars along the lower river (Sykes, 1937; Smith and Crampton, 1987; Beer, 1988).

Although impressive to humans, the dangers posed for desert fishes by upper limits of these variations are more imagined than real. The physical force of flooding rarely harms either individuals or populations (Meffe, 1984; Meffe and Minckley, 1987; Minckley and Meffe, 1987). Fishes apparently move to near the surface along shore even in canyons, thereby avoiding both the force of currents and molar action of transported bedload, as well as higher turbidities in deeper, turbulent channels. In wide places, they simply swim onto floodplains and then swim back as water recedes. Coarse, suspended sediments are similarly innocuous except, perhaps, through abrasion. High concentration of clays may suffocate fishes by clogging their branchial chambers (Wallen, 1951), but such has rarely been observed in western streams (Minckley, 1973).

A major seasonal problem may have been the food supply. Food may have been limiting during periods of high turbidity and bedload transport. As detailed in this chapter by Blinn and Cole, lower parts of large erosive streams are notoriously depauperate of fish foods. Algae and other primary producers are limited by turbidity and scour, and plankton is rare. Invertebrates need primary producers, detrital materials, or other animals to eat, and most are excluded from unstable bottoms anyway.

Conditions are quite different at low water. Coarse particles settle quickly, water clears to expose boulders and canyon walls to sunlight for consider able depths, and bars are stabilized and armored with gravel as declining discharges sweep away the sand. Such places provide substrate for biological colonization.

No studies are available for large unmodified rivers of the lower Colorado basin, but primary producers and stream invertebrates in small desert streams are remarkably resilient (Meffe and Minckley, 1987; Grimm and Fisher, 1989). Diatoms reappear a day after flash flooding, and complex algal communities reestablish in weeks (Fisher et al., 1982; Fisher, 1986). Insects with life cycles of days or weeks recolonize in a few days, and those with longer generation times reappear over a month or two (Bruns and Minckley, 1980; Gray, 1981; Gray and Fisher, 1981; Minckley, 1981). Many feed on detritus, finely ground from leaves, branches, and trunks of trees being carried to the sea (Minckley and Rinne, 1985). Thus, considering the predictably long periods of low discharge in the river, algae and invertebrates may have been in ample supply for much of the year. Added to this were terrestrial invertebrates (e.g., Tyus and Minckley, 1988) and diverse inputs from tributaries.

Despite these benefits of low discharge, drought is the single most dangerous time for fishes. Many western fishes appear to require little more than water to survive, but they do need water. In valley reaches, infiltration into deep, coarse alluvial fill robs the channel of surface flow, and intermittency or desiccation may result. High temperatures and oxygen depletion in the remnant pools become critical and lethal. On the other hand, these massive alluviated valleys, many of which are actually structural intermontane basins, also act as vast subterranean reservoirs, dammed by the bedrock through which the canyons are cut.

These reservoirs were the key to fish survival. They leaked downslope into canyon-bound reaches, where pools held water in scoured holes and shaded undercuts along cliffs, Subterranean water percolating through coarse alluvium tends to be cool, mixed, and rich in nutrients (Grimm et al., 1981); thus, canyons often provide salubrious, highly productive habitat if sufficient sunlight is available. Bedrock reaches are also rich in springs, adding security to the system. In the large and complex Colorado River basin, mainstream fishes had many canyon refugia and after a few weeks, at most, would have been saved from even the greatest regional drought by runoff from somewhere. Clearly it worked over the millennia, since some of the fishes have persisted since Miocene (Minckley, et al., 1986).

UNIQUENESS OF THE FISH FAUNA

The special nature of the Colorado River fish fauna was recognized early. Evermann and Rutter (1895, p. 475) listed 5 families, 18 genera, and 32 indigenous species, and wrote:

> Though the families and species . . . are very few, they are of unusual interest to the student of geographic distribution . . . over 78 percent of the species of fishes now known from the Colorado Basin are peculiar to it . . . a larger percentage of species peculiar to a single river basin than is found elsewhere in North America.

Subsequent work has not altered these conclusions. Miller (1959) reported 31 freshwater species, while Minckley et al. (1986) documented 32. Recognized endemism at the species level still hovers near 75%. and Carlson and Muth (1989) compiled 44 taxa, 93% endemic when undescribed forms and subspecies were included. Clearly, as a result of long isolation and special conditions, the Colorado River basin supports the most distinctive ichthyofauna in North America.

Larger fishes of the Colorado River mainstream share an intriguing, number of features (Hubbs, 1941; Miller and Webb, 1986). Their adult body sizes are large, and some species live exceptionally long lives. (All fish measurements reported here are for total length, from the extreme tip of the snout to the distal end of the caudal fin.) Body shapes are more fusiform and streamlined than most, with streamlining carried to extremes to include small depressed skulls, large predorsal humps or keels (or both), and elongated, pencil-thin caudal peduncles. Their eyes are small, the fins are expansive and often falcate (sickle shaped) with strong leading rays, and the skins are thick and leathery, especially on the head, anterior body, and leading edges of fins. Finally, the scales are tiny, deeply embedded in the skin, or sometimes essentially absent.

Most of these special features have been related to severity of habitat. Body and fin shape, structure, and size are construed as hydrodynamic adaptations for maintaining position and maneuvering in swift, turbulent currents. Large bodies and fins may, however, be as much a necessity to generate sufficient power to negotiate such places. Leathery skins with small, embedded, or reduced scales may minimize friction, counteract sediment abrasion, or provide a rigid external sheath to maximize muscle efficiency. Reduced eyes may be another way to avoid abrasion. Finally, long life seems adaptive to unpredictable environments, since the ability to reproduce spans decades rather than only a few years. On the other hand, large size (correlated with long life) scarcely seems adaptive to seasonally low discharge. Despite alternative possibilities, common trends in morphology across a number of unrelated taxa speak for commonality in other than phylogeny, and the river's harsh selective arena seems a reasonable choice.

HISTORIC REVIEW

Early Records and Surveys

Faunal remains in archaeological sites show that Colorado River fishes were caught and eaten by Indians (Miller, 1955; Euler, 1978; Miller and

Smith, 1984). Early canyon explorers ate them too, and valuable records appear in the accounts of John Wesley Powell (1875), Stegner, (1954), Robert Brewster Stanton's railway surveys (Smith and Crampton, 1987), the adventures of Ellsworth and Emery Kolb (Kolb and Kolb, 1914; Kolb, 1989), and others.

The earliest scientific collectors sampled tributaries (Baird and Girard, 1853a–c; Girard, 1857, 1859; Cope and Yarrow, 1875; Kirsch, 1889), the Colorado mainstream near Yuma (Abbott, 1860; Evermann and Rutter, 1895; Gilbert and Scofield, 1898; Chamberlain, 1904; Snyder, 1915), and at upstream crossings on the Grand (= Colorado) and Green (Jordan, 1891; Evermann and Rutter, 1895) rivers. Canyons remained inhospitable to humans until rubberized boats made whitewater rafting safe and reliable. Even with modern equipment, sampling is difficult at best, and the faunas of canyon-bound reaches of the river remain the least understood of all. Most species had nonetheless been collected and described before 1900 (Minckley and Douglas, 1991). The early surge of inquiry declined over almost four decades of complacency that followed Jordan and Evermann's (1896–1900) monograph "The Fishes of North and Middle America."

EVIDENCES OF FAUNAL CHANGE

Carl L. Hubbs and Robert R. Miller reinitiated studies of Colorado River fishes in the late 1930s. They began by producing revisionary works and compilations of records (Hubbs and Miller, 1941; Miller, 1943), descriptions of new taxa and life stages (Miller, 1946a; Winn and Miller, 1954; Miller and Hubbs, 1960), and records of hybrids (Hubbs et al., 1942; Hubbs and Miller, 1953), and they moved with time to authoritative biogeographic accounts (Hubbs and Miller, 1948; Miller, 1959). Scattered throughout these works were notes on faunal declines, and Miller (1946b) published an early plea for study of native fishes before further alterations of the large western rivers were undertaken.

Dill's (1944) survey of the lower Colorado River was the first to provide insight on both native and introduced fishes downstream from the new Boulder (= Hoover) and Parker dams. He noted reductions in native species attributed to environmental changes associated with damming. Wallis (1951) considered the fauna "in urgent need for further research, because so many forces are fast exterminating it." Jonez et al. (1951) and Jonez and Sumner (1954) also expressed concern for native fishes in the face of rapid environmental change.

Alien fishes attracted early attention (Dill, 1944; Beland, 1953b; Hubbs, 1954). Reservoirs changed the river in ways that enhanced lentic-adapted, nonnative species (Jonez et al., 1951; Beland, 1953a; Kimsey, 1958; Nicola, 1979), and reservoir sportfisheries became important regional resources (Moffett, 1942, 1943; Wallis, 1951; Jonez and Sumner, 1954). A remarkable array of both native and nonnative species were used as bait (Miller, 1952), and bait and forage fishes escaped or were intentionally stocked to join and feed expanding game fish populations (Hubbs, 1954; Kimsey et al., 1957; LaRivers, 1962; U.S. Fish and Wildlife Service, 1980, 1981).

By the 1960s, although essentially invisible to the untrained eye, indigenous fishes of the lower Colorado River had been largely replaced by exotic species. Miller (1961) wrote of dramatic changes in abundance and distribution and of local extirpation of native forms. At this same time, Glen Canyon, Flaming Gorge, Navajo, and other major dams authorized by the Colorado River Storage Project Act of 1956 were also nearing completion. These were far from invisible. The magnitude of change was finally realized, and alarms began to sound in an emerging conservation community. The Colorado River had indeed been tamed, its wildness was lost except in the most isolated and inaccessible reaches, and the public was stirred to react. Resistance against other dams was led by the Sierra Club, and conservationists voiced their opposition to further modifications (Fradkin, 1981).

In addition to this controversy, almost 700 km of the Green River system above the new Flaming Gorge Dam was poisoned in 1962 to clear the way for an introduced trout fishery (Holden, 1991). Some of the targets were native fishes. The operation went awry, and fishes were killed far downstream through Dinosaur National Monument (Miller, 1963a, 1964). This event, possibly more than anything else, solidified the resolve of those protective of native fishes.

In addition to making available funds for reservoir planning and construction, the storage act provided for evaluation of the archaeological significance of areas to be inundated. Preimpoundment surveys conducted along with archaeological salvage operations included biological collections for use in interpreting paleo-Indian ecology. Studies were made in the Flaming Gorge Reservoir basin (Dibble and Stout, 1960; Woodbury, 1963), Navajo basin (Pendergast and Stout, 1961), and the future basin of Lake Powell (Woodbury, 1959; McDonald and Dotson, 1960). Marble and Grand canyons were ignored since they were not to be directly affected. By the time Miller (1968) and Suttkus and colleagues (Suttkus et al., 1976; Suttkus and Clemmer, 1979) began sampling in 1968 and 1970, respectively, the downstream impacts of Glen Canyon Dam were already evident.

In 1963, partially in response to public outcry over the poisoning, agencies such as the National Park Service, Fish and Wildlife Service, and state conservation departments began studies of Green River fishes (Vanicek, 1967; Vanicek and Kramer, 1969; Vanicek et al., 1970). Such research expanded elsewhere as new legislation came to bear in the late 1960s (Holden, 1973; Holden and Stalnaker, 1975). Disappearing species became rallying points for the Endangered Species Protection Act of 1966, which evolved to the Endangered Species Act of 1973. Recognition that habitat was being lost at an unacceptable rate stimulated the National Environmental Protec tion Act of 1969, which mandated assessment and disclosure of impacts of federal projects. After 1966, lists of species in jeopardy served to focus research and management efforts and agencies such as the Bureau of Reclamation became involved to satisfy legal requirements for project construction and operations.

Ongoing research has since documented the status and ecology of fishes targeted by official listings. Some resulted in major reports (Minckley, 1979; Carothers and Minckley, 1981; Miller et al., 1982b–c; Maddux et al., 1987; Tyus et al., 1987; Ohmart et al., 1988), only excerpts of which have appeared in the open literature. Smaller, more specific projects dealt with species' biology or habitat; many of these are cited in recovery plans (U.S. Fish and Wildlife Service, 1989b–d) or status reports for rare species (Seethaler, 1978; McAda and Wydoski, 1980; Minckley, 1983; Kaeding and Osmundson, 1988; Minckley et al., 1991; Tyus, 1991). Reviews varied from annotated bibliographies (Wydoski et al., 1980), through edited symposia (Spofford et al., 1980; Miller et al., 1982a; Adams and Lamarra, 1983; Minckley and Deacon, 1991), to contributions dealing with the fauna (Deacon, 1968, 1979; Joseph et al., 1977; Holden, 1979; Behnke and Benson, 1983; Stanford and Ward, 1986c) and its ecosystem (Deacon and Minckley, 1974; Ono et al., 1983; Williams et al., 1985; Stanford and Ward, 1986a,b; Carlson and Muth, 1989). In short, a wealth of information now exists on Colorado River fishes.

NATIVE FISHES

Six of eight fishes native to Grand Canyon National Park (Table 7-1) are endemic. Speckled dace and roundtail chub are known from adjacent rivers, and the latter, known only from a few specimens (C. O. Minckley, 1980), is excluded from further consideration. Four of the remainder, humpback chub, bonytail, Colorado squawfish, and razorback sucker, are listed or proposed as endangered by the Department of the Interior (U.S. Fish and Wildlife Service 1989a, 1990). Of these, only the humpback chub (Figure 7-1) persists as a reproducing population. The other three are extirpated or exceedingly rare. Speckled dace, flannelmouth sucker, and bluehead sucker remain relatively common (Minckley, 1985).

Most early accounts of fishes in the Colorado River were for large species sought for food, e.g., "Colorado River salmon" (squawfish) was on the menu of Christmas dinner for the Stanton Party in 1889 (Measeles, 1981; Smith and Crampton, 1987). Most records were more informal. When Kolb and Kolb (1914, p. 123) heard splashing near their camp at the Little Colorado River in 1911. they wrote:

> . . . the fins and tails of numerous fish could be seen above the water. The striking of their tails had caused the noise we had heard. The 'bony

TABLE 7-1 Common and scientific names of native and introduced fishes recorded from Grand Canyon National Park, Arizona. Those taxa marked with an asterisk (*) are listed or proposed for listing as endangered by the U.S. Department of the Interior.

CLUPEIDAE, shads—introduced	
Threadfin shad	*Dorosoma petenense* GHnther
SALMONIDAE, salmons and trout—all introduced	
Apache trout	*Oncorhynchus apache* Miller
Cutthroat trout	*O. clarki* Richardson
Silver Salmon	*O. kisutch* Walbaum
Rainbow trout	*O. mykiss* Walbaum
Brown trout	*Salmo trutta* Linnaeus
Brook trout	*Salvelinus fontinalis* Mitchill
CYPRINIDAE, minnows	
Native species	
*Humpback chub	*Gila cypha* Miller
*Bonytail	*G. elegans* Baird and Girard
Roundtail chub	*G.r. robusta* Baird and Girard
*Colorado squawfish	*Ptychocheilus lucius* Girard
Speckled dace	*Rhinichthys osculus* Girard
Introduced species	
Common carp	*Cyprinus carpio* Linnaeus
Red shiner	*Cyprinella lutrensis* Baird and Girard
Golden shiner	*Notemigonus crysoleucus* Mitchill
Fathead minnow	*Pimephales promelas* Rafinesque
Redside shiner	*Richardsonius balteatus* Richardson
CATOSTOMIDAE, suckers—all native	
Flannelmouth sucker	*Catostomus latipinnis* Baird and Girard
Bluehead sucker	*Pantosteus discobolus* Cope
*Razorback sucker	*Xyrauchen texanus* Abbott
ICTALURIDAE, bullhead catfishes—all introduced	
Black bullhead	*Ameiurus melas* Rafinesque
Channel catfish	*Ictalurus punctatus* Rafinesque
FUNDULIDAE, killifishes—introduced	
Plains killifish	*Fundulus zebrinus* Jordan and Gilbert
POECILIIDAE, livebearers—introduced	
Mosquitofish	*Gambusia affinis* Baird and Girard
CENTRARCHIDAE, sunfishes—all introduced	
Green sunfish	*Lepomis cyanellus* Rafinesque
Bluegill	*L. machrochirus* Rafinesque
Largemouth bass	*Micropterus salmoides* Lacepede
PERCICHTHYIDAE, temperate basses—introduced	
Striped bass	*Morone saxatilis* Walbaum

tail' were spawning. . . . The Colorado is full of them; so are many other muddy streams of the Southwest. They seldom exceed 16 inches in length, and are silvery white in color. With a small flat head somewhat like a pike, the body swells behind it to a large hump.

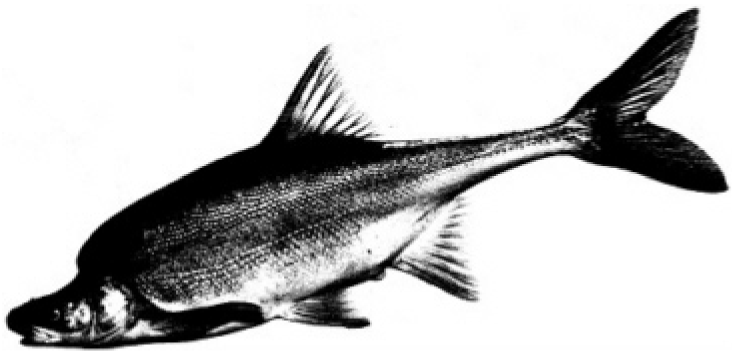

Figure 7-1
Male humpback chub, ca. 38 cm long, captured from the Little Colorado River, Arizona; photograph by J. N. Rinne at Willow Beach National Fish Hatchery.

Suttkus and Clemmer (1977) believed the fish to be humpback chubs rather than bonytail, which seems likely. True bonytail (Figure 7-2) were better described by Dellenbaugh (1984, p. 15) from the Green River:

. . . a fish about ten to sixteen inches long, slim with fine scales and large fins. Their heads came down with a sudden curve to the mouth, and their bodies tapered off to a very small circumference just before the tail spread out.

Another quotation from Dellenbaugh (1984, p. 98) introduces the Colorado squawfish (Figure 7-3 and 7-4). The incident occurred near the present town of Green River, Utah, in 1871; Minckley (1973, p. 124) erred in attributing it to Grand Canyon in 1872:

He [a member of the second Powell Expedition] thought his precious hook was caught on a snag. Pulling gently in order not to break his line the snag lifted with it and presently he was astounded to see, not the branch of a tree or a waterlogged stick, but the head of an enormous fish appear above the surface. . . . Casting again another of the same kind came forth and then a third. The longest . . . was at least thirty or thirty-six inches with a circumference of fifteen inches. The others were considerably shorter but nevertheless very large fish.

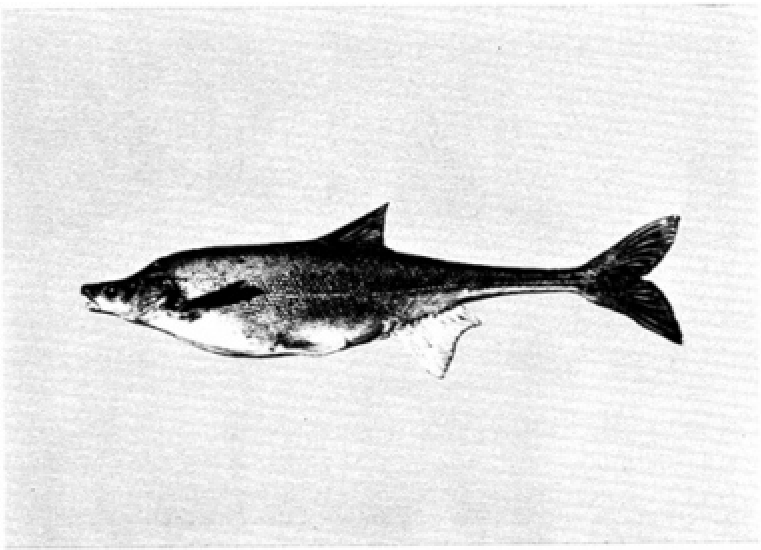

FIGURE 7-2
Female bonytail, ca. 50 cm long, trammel-netted from Lake Mohave, Arizona-Nevada; photograph by W. L. Minckley.

Colorado squawfish were familiar to all of the early canyon explorers. Stanton recorded "large" or "huge" fish caught in the Green and Colorado rivers (Smith and Crampton, 1987). Dellenbaugh (1984, facing p. 102) published a photograph of two large ones taken by the Stanton party in 1889. In southern Wyoming in 1911, Kolb (1989, p. 15)

. . . caught sight of fish gathered in a deep pool, under the foliage of a cottonwood tree which had fallen into the river. Our most tempting bait failed to interest them; so Emery, ever clever with hook and line, 'snagged' a catfish . . . for salmon bait, a fourteen-pound specimen rewarding our attempt. . . . They sometimes weigh twenty-five or thirty pounds, and are common at twenty pounds; being stockily built fish, with large, flat heads.

I found no references to other species in this kind of older literature, although hungry explorers undoubtedly ate any large fish. But suckers rarely take a hook, and speckled dace (Figure 7-5) are too small to be of much culinary interest.

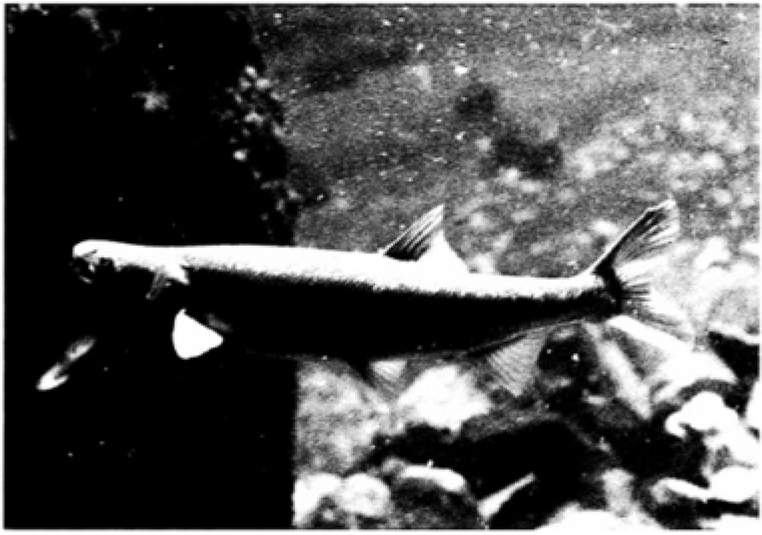

FIGURE 7-3
Hatchery produced Colorado squawfish, ca. 50 cm long (1974 year class), on display at the Arizona-Sonora Desert Museum, Arizona; photograph by J. N. Rinne.

A few scientific collections were made specifically in Glen and Marble/ Grand canyons prior to the 1960s. The survey of Glen Canyon in 1958 included 27 sites, mostly in tributaries (Smith, 1959; Smith et al., 1959; McDonald and Dotson, 1960). Seventeen species were taken, of which roundtail chub, Colorado squawfish, speckled dace, flannelmouth, bluehead, and razorback suckers were native. Ten nonnatives were dominated by fathead minnow, carp, channel catfish, and green sunfish.

One specimen caught on hook and line near Bright Angel Creek in Grand Canyon was used with two others from unknown sites to describe the humpback chub (Miller, 1946a). Other species known from Marble/Grand canyons at that time (Miller, 1946a), razorback and bluehead suckers, bonytail, and channel catfish, had also been caught by anglers. Anne and 1. A. Rodeheffer seined speckled dace, squawfish, flannelmouth and bluehead suckers, and nonnative channel catfish in the Colorado and Paria rivers near Lees Ferry in 1934; C. H. Lowe caught dace from Big Nankoweap Creek in 1953; and O. L. Wallis secured a humpback chub near Spencer Creek in

1955 (University of Michigan Museum of Zoology catalog of specimens). Shortly after closure of Glen Canyon Dam, gill-net samples in and below the filling reservoir caught only large species, humpback and roundtail chubs, bonytail, and apparent hybrid chubs (Holden, 1968; Stone, 1965–1969, 1971, 1972; Stone and Rathbun, 1967–1969; Holden and Stalnaker, 1970). Bluehead and flannelmouth suckers were also there, as were introduced carp and channel catfish (unpublished data).

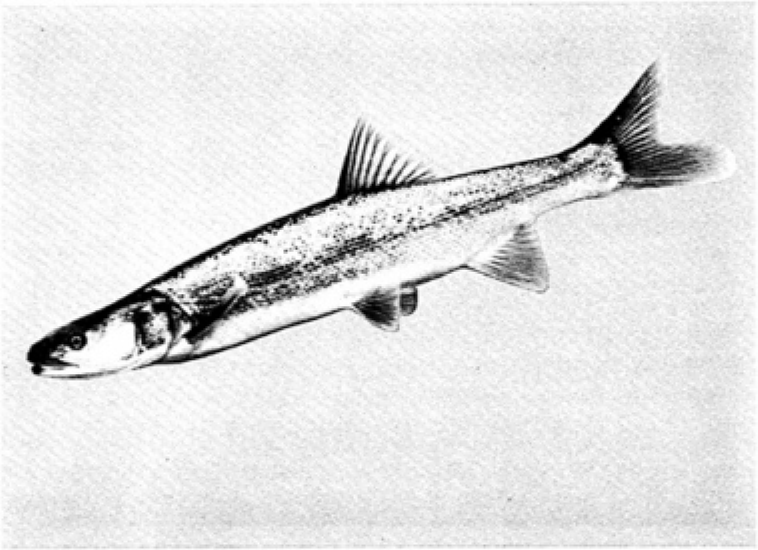

FIGURE 7-4
Hatchery produced Colorado squawfish, 42 cm long (1974 year class); photograph by J. E. Johnson.

THE FISH COMMUNITY

As already noted, much is known of the ecology and distribution of Colorado River fishes. Unfortunately, however, many data are in state and federal agency reports, difficult to find and obtain, and mostly dealing with limited geographic areas. A review of the fish fauna of Marble/Grand canyons was thus difficult to prepare without an overburdening volume of citations. I attempted to avoid this problem by presenting species accounts in the Appendix, which may be consulted for details.

Under pristine conditions, most fishes of the lower Colorado River mainstream probably lived in valley reaches. Canyons would have been most densely populated in wide places near inflowing streams and in tributary mouths. During low flow, most species (or at least larger individuals) moved into canyons to avoid declining water levels or high summer water temperatures (Siebert, 1980).

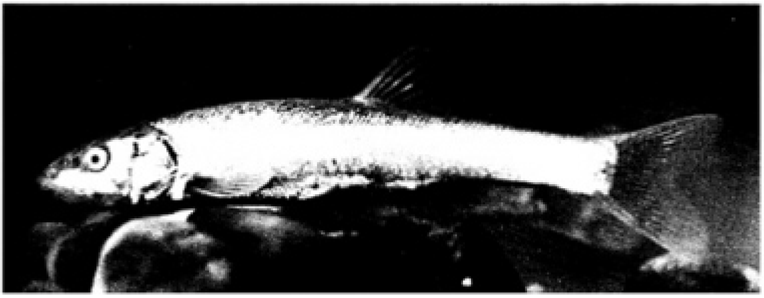

Figure 7-5
Speckled dace, 62 mm long, from the Virgin River, Arizona; photograph by J. N. Rinne.

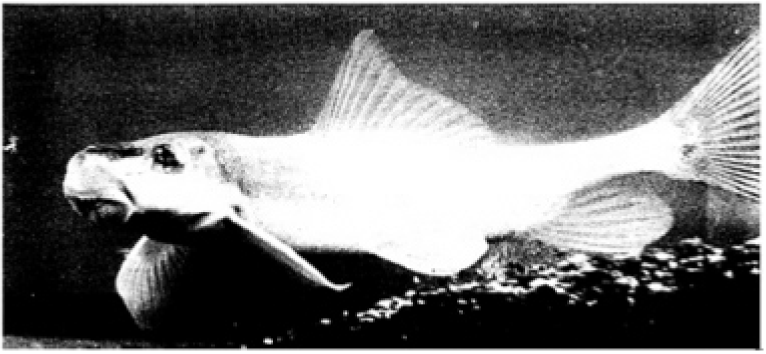

FIGURE 7-6
Flannelmouth sucker, ca. 40 cm long, from the Virgin River, Arizona; photograph by J. N. Rinne.

Adults of each species lived in proximity to their preferred foods and among physical habitat features commensurate with their sizes and morphologies. Large squawfish occupy quiet places along shore, often near overhead cover such as logs or other debris or in "pockets" between boulders. Flannelmouth suckers (Figure 7-6) stay on the bottom in deep, quiet or slow-moving water, and they feed in eddies and along shorelines of pools and riffles. Large blueheads (Figure 7-7) also occupy deeper places except when feeding, moving to hard bottoms in shallows to graze. Razorback suckers (Figures 7-8 and 7-9) occupied near-bottom space, most likely in open, flowing channels but also in backwaters and eddies when available. I suspect adult bonytails to have stayed mostly in the water column in the channel with razorbacks. Deep pools and eddies of whitewater canyons support humpback chubs, alone except for transients of other species. Roundtail chubs are also common in such places in the upper basin: how the last two chubs partition habitat space is unknown. Speckled dace stay near the bottom in water a few centimeters deep along shorelines, on riffles, and in tributary mouths.

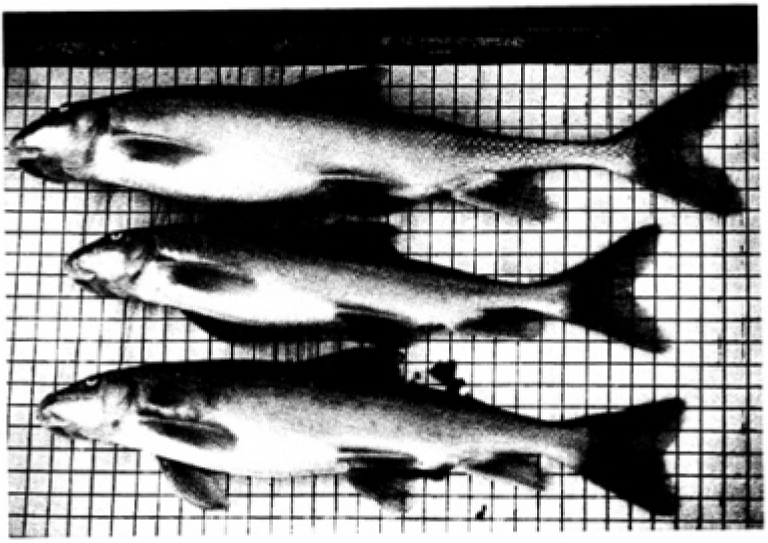

FIGURE 7-7
Bluehead suckers, 38 to 45 cm long, from the Green River, Utah; photography by W. L. Minckley. These specimens, taken at the same locality, demonstrate the remarkable variation in caudal peduncle length and diameter seen in mainstream populations.

Apparent trophic relations also seem fairly straightforward (Minckley, 1979), characterized by qualitative (kind) and quantitative (size) differences in foods and spatial segregation in feeding. Adult squawfish eat other fishes. Each of the three suckers is adapted differently: flannelmouth for feeding on small aquatic insects and other benthic animals; blueheads for scraping algae; and razorbacks with protrusible mouths and special gill rakers for sieving plankton or detritus. Studies of food habits tend to bear out the interpretations from morphology for all of these species. Humpback chubs and bonytail both tend to be insectivores, eating both large and small terrestrial and aquatic invertebrates. The former must feed both in the water column and on bottom in deep eddies and zones of turbulence, and the latter feed in midwater and near surface in smooth-flowing channels. Speckled dace also are insectivores or facultative omnivores, delving over and into bottom interstices in search of invertebrates and other organic materials.

FIGURE 7-8
Razorback sucker, ca. 50 cm long, on display at the Arizona-Sonora Desert Museum, Arizona; photograph by J. N. Rinne.

By and large, reproductive sites seem more similar among species than are habitats and food habits. Perhaps the requirements for egg and larval development necessitate relatively swift current and clean, unconsolidated gravel substrates. The three suckers and speckled dace reproduce in spring on gravel or cobble riffles. Razorbacks spawn earlier than the others, and dace use shallower places and tributary mouths. Squawfish also spawn on gravel or cobble bottoms in current, in late spring or summer. We know nothing of bonytail spawning other than in artificial lakes or ponds, and humpbacks are even more of a mystery. Both breed in June-early July in the upper basin and in March–May downstream.

Only the squawfish has evolved a life history that includes long spawning migrations to precise sites that are presumably identified by olfaction (Tyus, 1985, 1986). Other species may select suitable spawning sites by cues such as substrate, depth, current, or proximity. In the upper basin, radiotagged humpbacks rarely move more than 1 km from the point of tagging, and they presumably spawn there. However, tagged humpback chubs move upstream and downstream for more than 10.0 km in the Little Colorado River, and back and forth from there into the mainstream Colorado. Some humpbacks tagged in the Little Colorado returned as long as 8 years later (C. O. Minckley, 1989; Kubly, 1990). The interrelations of movements and reproduction in Grand/Marble Canyon humpbacks are not yet understood. Speckled dace enter tributaries to spawn, both in Marble/Grand canyons and elsewhere. Razorback suckers do not appear to make directed movements to specific sites for reproduction (Minckley et al., 1991), yet only a few spawning sites are known in the Green River (Tyus, 1987). Razorbacks in Lake Mohave, Arizona-Nevada, spawn at various places in different years and perhaps in the same year (W. L. Minckley and P. C. Marsh, unpublished data).

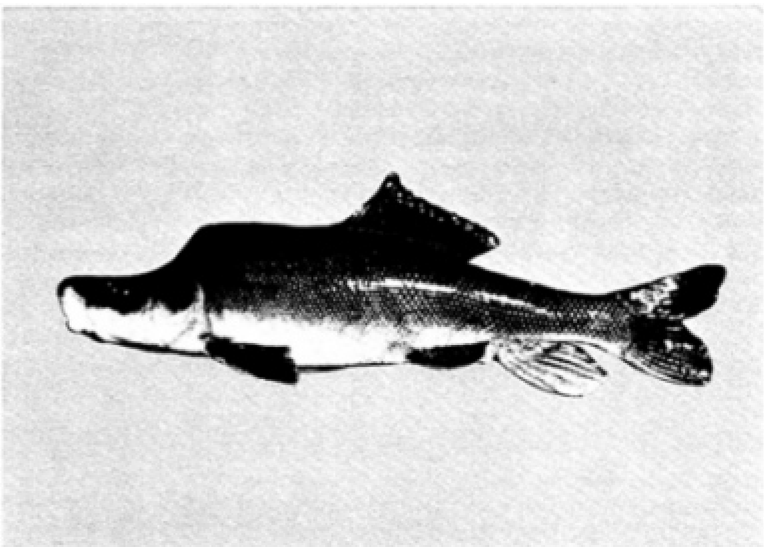

FIGURE 7-9
Male razorback sucker, ca. 50 cm long, trammel-netted from Lake Mohave, Ariona-Nevada; photograph by W. L. Minckley.

Different life stages of fishes have different ecologies, and perhaps especially so in the Colorado River, where only a few species are present in a large and diverse environment. The pattern of downstream movement of young squawfish to nursery areas, growth, and then redispersal upstream as young adults exemplifies the use of almost all available habitat by a single species. Young of other species, including humpback chubs from canyons and dace from tributary mouths, also seem to travel downflow along shore-lines and into embayments and backwaters at first and then move with increased age and size to occupy their adult niches in the channel.

REASONS FOR DISAPPEARANCE OF THE FAUNA

Nonbiological Changes

Human modification of the Colorado River basin is profound. The stream sustains more consumptive water use than any other river in the United States (Pillsbury, 1981), and less than 1% its of virgin flow now reaches the mouth (Petts, 1984). At least 117 impoundments with individual capacities greater than 1.0×10^6 m^3 have been built in the upper basin alone, and more than 40 diversions export water to adjacent basins (Bishop and Porcella, 1980). The lower part of the basin is even more dramatically changed. Examination of the impacts of this development from other than the biological perspective by Fradkin (1981), Worster (1985), Reisner (1986), and Weatherford and Brown (1986) are required reading for anyone trying to understand the magnitude of alteration to the river and its tributaries.

In spite of this high level of exploitation. I am hard pressed to attribute the general disappearance of Colorado River fishes to physical changes in habitat. The basin remains large and diverse. Almost all of the native species were wide-ranging, including those now classed as endangered. Squawfish, bonytails, and razorbacks all historically occupied ~10° of latitude, from southern Wyoming to Mexico, and humpback chubs lived from to Wyoming to below Lake Mead. The humpback chub may be specific in its habitat needs, but the Little Colorado and Yampa rivers are certainly very different in size and nature from the Green and Colorado mainstems, and the species persists in all four. Upstream from dams, discharge, sediment load, and other factors still vary over many orders of magnitude. I am also impressed by the persistence of this native fauna over geologic time (Minckley et al., 1986) and agree with M. L. Smith (1981) in considering all of the species as generalists. I seriously doubt that physicochemical changes wrought by humans in less than 100 years equal those occurring since Miocene, which began 20+ million years ago.

The fact that these fishes adapt to, reproduce in, and mature in a spectrum of artificial habitats also supports a hypothesis of broad ecological tolerances. They have proven relatively simple to maintain and rear in captivity (Rinne et al., 1986; Johnson and Jensen, 1991). Although changes in a system may alter or invalidate cues required for reproduction or survival, these fishes succeed in places where habitat-mediated cues reinforced over evolutionary time (other than seasonal temperatures, day lengths, etc.) cannot exist.

Only two direct effects of dams—blockage of spawning migrations and depression of summer water temperatures—seem sure to extirpate most native species, and I am not fully convinced these can be singled out. For example, squawfish move both upstream and downstream to reach their spawning sites (Tyus, 1986; Tyus and Karp, 1989). Assuming that the site itself was not destroyed, a dam would only exclude the downstream part of a stock, and fish from upstream should persist. I argue later that loss of nursery areas was more important in the decline of this species than was interdiction of spawning migrations.

Water temperature too low for reproduction or larval development clearly results in loss of populations and is the culprit excluding natives from Marble/Grand canyons, yet less than half of the available mainstream is rendered too cold by hypolimnetic waters or physically drowned by reservoirs. Why then has the entire fish fauna collapsed? I forward an hypothesis, perhaps untestable in nature to answer this question: the introduction and enhancement of nonnative fishes as a result of river alterations forced the native species to extinction. To add salt to an open wound, this is a problem for which we were poorly prepared and one that we have not yet resolved to address.

Biological Changes

Remarkable numbers of nonnative fishes have been intentionally and inadvertently stocked into the Colorado River. Introductions and impacts of exotic fishes in North America were reviewed in Courtenay and Stauffer (1984), and many other works list and discuss such species in the Colorado River basin (e.g., LaRivers, 1962; Sigler and Miller, 1963; Minckley, 1973, 1982; Miller et al., 1982a; Moyle, 1978). Early stockings were of preferred food fishes of the time, including carp, buffalofish, shads, various salmonids, and even eels. At least 20 species of nonnative fishes were planted in Utah prior to 1900 (Sigler and Sigler, 1987); catfishes and carp were well established by then in the lower Colorado (Chamberlain, 1904). As time went on, stocking shifted toward predatory species for reservoir sportfisheries, additional bait species escaped, and forage fishes were introduced. Tropical species appeared mostly after World War 11, planted in attempts at vegetation control or by mistake as escapees from aquaria.

Many aliens disappeared, but others established. The original fauna of 30 or so native species in the Colorado basin has increased to 80 or more, including salmonids from the Pacific Coast, Great Lakes, and Europe; minnows from as far away as Europe and Asia and as near as the adjacent Great Basin; minnows, catfishes, sunfishes, and basses from the Mississippi-Rio

Grande system; livebearers from Mexico; cichlids from Africa and Central America; anadromous sea bass from the Atlantic (in part via California); and others.

Nonnative fishes have invaded essentially every habitat and continue to do so as species disperse from place to place and others appear. The Colorado River has become a crowded world. Larvae of squawfish and other natives share backwaters behind sandbars with many nonnative young (Karp and Tyus, 1990). Species piscivorous when young (especially green sunfish) or remaining small as adults (e.g., the voracious mosquitofish) are now there to meet and eat them. Juvenile squawfish may use abundant larvae, young, and adults of nonnative minnows as food, and adults seem to have little competitive difficulty, as yet, with comparable piscivores like northern pike and walleye (Tyus, 1991), but negative interactions seem inevitable.

Today, if larval native fishes move downstream to an ancestral nursery they find themselves instead in a reservoir. Predatory sunfish live along shorelines, and schools of planktivores such as threadfin shad serve as competitors (and perhaps predators) in open water. In addition, midwaters and shorelines in valley reaches are swarming with one or another kind of alien minnow. Sand, redside, and red shiners and fathead minnows are common, the first two upstream from Lake Powell and the last two throughout the river. Channel catfish are more prevalent in eddies of whitewater canyons than humpback chubs. Further examples seem unnecessary. The abundant presence of introduced fishes can only reduce space, food, and survivorship of the natives.

We are unsure of the specific causes of native fish declines, for even the most apparent interactions. This is an area needing serious research. Spikedace and woundfin, both federally listed minnows of the lower Colorado basin, consistently disappear as red shiners invade and become abundant (Minckley and Deacon, 1968; Deacon, 1988; Marsh et al., 1989). Attempts to quantify interactions for food and space have failed, except in pointing out some of the subtle ways the nonnatives may replace (or displace) the native forms (Abarca, 1989; Marsh et al., 1989). Mosquitofish eat the young of native, endangered topminnows and remove the fins from adults so they succumb to secondary infections (Meffe, 1983, 1985). Flathead catfish are invading the Salt River Canyon in Arizona, followed closely by disappearance of the native fauna (D. A. Hendrickson, personal communication). Indigenous fishes may simply be naive to alien predators (Meffe, 1983, 1985; Minckley, 1983), but we are not even sure of this.

Few things seem to help native fishes survive the onslaught of alien forms, aside from strong evidence that flooding in canyons displaces nonnative fishes while native species are unaffected. In fact, native fishes are often enhanced by flood removal of predators and competitors (Minckley and

Meffe, 1987). The effect is temporary, since the canyons are soon reinvaded by alien fishes from populations protected in reservoirs and ponds upstream.

Part of the present ecology of the Colorado River includes fisheries for nonnative trouts. Fortunately, there seem to be few conflicts between trouts and indigenous, warmwater fishes that result in demise of the latter, mostly because of their separate temperature requirements. Few realize that trout were introduced into cool tributaries of the Marble/Grand canyons system in the 1920s, long before any dams (McKee, 1930; Brooks, 1931; Williamson and Tyler, 1932; U.S. Fish and Wildlife Service, 1980, 1981). From there they spread to other tributaries through the Colorado River in winter; summer temperatures in the river were too warm for them to survive. Today, trout permanently inhabit the mainstream because of cold, epilimnetic water from Lake Powell, the same reason the native, warmwater fishes disappeared. Piscivorous brown trout may remove high-altitude minnows such as spikedace through predation, and nonnative trouts compete with, prey upon, and hybridize with native trouts, but these subjects do not pertain to the Colorado River mainstream.

Tailwater trout fisheries in the desert southwest started with rainbows stocked immediately after Boulder (= Hoover) Dam was closed in 1935 (Moffett, 1942). The fish grew rapidly to large size, and Eicher (1947) estimated that ~9,000 kg was harvested in 1946. Fish averaged ~40 cm long, varying upward to 60 cm. Problems were the same as perceived today for the fishery below Glen Canyon Dam—an apparent scarcity of food (Moffett expressed amazement at the amount of filamentous algae consumed), questions of instream reproduction versus stocking in maintaining the population, and possible impacts of river fluctuations. Hoover Dam has multiple penstocks, and warm downstream temperature was also a potential problem when higher-elevation water passed through the turbines.

When Lake Mohave was closed in 1954, the riverine trout fishery below Lake Mead was reduced in size (Wallis, 1951; Jonez and Sumner, 1954). However, a "layered" fishery soon developed, with fast-growing rainbow trout living below the thermocline in summer (throughout the system in winter) and warmwater species in the epilimnion. Trout were planted later in Lake Mead to create another, highly successful layered fishery (Allen and Roden, 1978) that was destroyed by the proliferation of predatory striped bass stocked to form another new sportfishery in the late 1960s (Baker and Paulson, 1983).

No time was wasted in stocking trout in tailwaters of Flaming Gorge and Glen Canyon reservoirs. Flaming Gorge was further retrofitted with variable intake levels in the early 1980s, so that warm, near-surface water could be released in summer to enhance downstream trout (Johnson et al., 1987). The hypolimnion of Flaming Gorge Reservoir is 4.0 to 6.0°C year-around, too cold for even salmonids to achieve their growth potentials. Both the

National Park Service and Arizona Game and Fish Department stocked trout as soon as Glen Canyon Dam was closed in 1963. Survival and growth were high, and the fishery expanded to "world-class" status. It has declined a bit in quality but remains regionally substantial and important (Janisch, 1985; Taubert, 1985). Because of persistence of cold water through most of Marble/ Grand canyons, trout remain common through more than 300 km of river (Maddux et al., 1987), although few are harvested downstream from Lee's Ferry because of limited access. Some of the economic (Richards and Wood, 1985), sociological (Caylor, 1986), and biological aspects (Persons et al., 1985; Montgomery et al., 1986; Maddux et al., 1987; Kondolf et al., 1989) of this coldwater fishery sandwiched between warmwater habitats have been studied. Unfortunately, most information remains in unpublished agency reports, yet to be reviewed and summarized.

DISCUSSION

Management Considerations

Native fishes of the American West will not remain on earth without active management, and I argue forcefully that control of nonnative, warmwater species is the single most important requirement for achieving that goal. Despite appearances, no part of the river is natural so long as alien fishes predominate. The wishes of agencies and individuals to maintain native fishes in "natural" habitats cannot be realized, since none is natural so long as nonnative fishes are present. Removal of nonnative fishes from entire watersheds may be the only way to conserve some native populations, but there is no known way to remove established alien species from so large and complex a system as the Colorado River. On the other hand, as judged from research over the past 25 years (Minckley and Deacon, 1991), many habitats will continue to support natives if nonnative species are suppressed; management efforts must be tailored to minimize their impacts.

This argument is not to belittle needs to preserve those parts of the system which retain their natural physicochemical and biological attributes. Upstream, instream, and downstream modifications that influence such reaches must be carefully screened for operational ways to maintain and increase naturalness. We must seize every opportunity, for example, to perpetuate and enhance flow through water conservation and careful scrutiny for confirmation of need. When water is to be passed through a reach for downstream use, delivery should be in such a way as to mimic natural patterns and thus enhance habitats and native fishes. In modified reaches, new (and old) techniques of habitat reconstruction can be applied, varying from removal of regulation structures, a preferred alternative of many workers, to allowing them to fall into disrepair (Swales, 1989). Building additional structures that produce greater heterogeneity, a preferred alternative of development agencies, may or may not be advisable. Nonetheless, some developments for aquaculture (Welcomme, 1989), e.g., excavation of floodplain lakes and marshes, are applicable to recovery of Colorado River fishes. National wildlife refuges and other federal and state reserves already dedicated to waterfowl or other biological resources are already available (Minckley, 1985; Minckley et al., 1991), if and when approval of their use for native fishes is realized.

In some cases, modifications of existing structures may not be advisable. For example, retrofitting Glen Canyon Dam with variable intake levels to allow manipulation of downstream water temperatures (U.S. National Park Service, 1977) might well open a Pandora's box. Warming the water in Marble/Grand canyons too much would result in replacement of trout by warmwater species, violating policies of agencies charged with managing the sportfishery (Arizona Game and Fish Department, 1978) and scarcely being appreciated by sportsmen. One of the last things needed is a pitched battle between sportsmen protecting trout and conservationists bent on recovery of an endangered fauna. Warming would nonetheless allow reintroduction of squawfish and bonytail, with a chance for reestablishment, and might stimulate recruitment by the remnant populations of humpback chub and razorback suckers. Other native fishes could be benefited as well.

However, since the cold water of today is as large a deterrant for nonnative warmwater species as for natives, the former would also be enhanced (U.S. Fish and Wildlife Service, 1978). Miller (1968) caught more kinds and far more individuals of nonnative fishes in 1968, before extremely high, cold discharge, than were taken in later years. They had already invaded Grand/Marble canyons from both upstream and downstream and were forced either out of the system or to lower population levels as mean temperatures dropped. New predators are also present since the 1960s—striped bass both upstream and downstream and flathead catfish downstream of Lake Mohave, but moving inexorably upstream through unauthorized and illegal stocking. Warm water would benefit these fishes, which would in turn deter establishment of reintroduced stocks of natives and contribute to extirpation of the natives that remain. Clearly, maintaining native fishes in the region is complex, and the effort requires careful foresight and planning.

Politics of Conservation

Advocates of natural habitats and native fishes must deal with conservation at a number of levels, many of which are conflicting or otherwise difficult to resolve. First, aquatic habitats and fishes are not treated the same as other managed habitats and species. Agencies do not hesitate to exclude the public from an area near a bald eagle nest, remove feral burros because they compete with native bighorn sheep, or kill coyotes to lessen predation on American antelope fawns. The public, with some notable exceptions, goes along with these decisions and actions, partially because people sympathize with the species or life stage being protected. People do not identify with fish species or life stages, and they must be educated to do so. Thus, with few exceptions, agencies in the Southwest do not identify needs to protect spawning habitat or buffer spawning fishes from human harassment, nor do agencies regulate or prevent stocking of game or forage fishes that compete with or prey on natives or manipulate the take of large predators (by liberalizing size and creel limits, for example) to enhance a native form. Most fishes remain as commodities managed for catching and eating, especially if they are accessible, pretty, large, and tasty. Native species remain unknown despite legislation demanding their advertisement, management, and conservation.

Recognition that resource development is often incompatible with native animals and plants resulted in legislation protecting them, thereby regulating development. Thus, where researchers in the past sought answers to questions in pursuit of independent knowledge, today's workers are driven by mandate. Generalizations rarely come from such studies because of their short-term, problem-solving orientation. Research on perceived problems, directed and funded by agencies afflicted by the same problems, is always suspect and short term; answers may be obtained that further goals of projects that caused the problem, and frequently by personnel of the project itself. Only the most objective, impersonal, and highly trained investigators can do a creditable job under such circumstances. Recommendations of the National Research Council (1987) for participation by external, senior scientists in major environmental studies reflect a general concern for this situation.

A third problem centers on the information from agency-mediated studies becoming short-circuited into a voluminous and difficult-to-access "gray" literature. Changes in career emphasis have created a cadre of nonacademic and nonindustrial professionals who communicate their research findings in unpublished reports. Such reports are preliminary in nature, or prepared under deadlines, and so information may be presented partially or prematurely. Yet agencies demand such documents to account for expenditures, guide policies, and justify their actions. Most of these documents never reach the open, published literature. And only in the open literature are methods, data, and ideas subject to the benefits of peer review and criticism, interpretations sharpened, and gaps in information defined. Symposia like those of Miller et al. (1982a) on native fishes of the upper Colorado River basin and Minckley and Deacon (1991), reviewing management efforts for the western fish fauna, help in this regard.

Fourth, I reemphasize that far more attention must be paid the role of nonnative organisms in the displacement and replacement of native species. The Colorado River downstream from Lake Havasu has the dubious distinction of being the world's only major stream populated by an entirely alien fish fauna, and we have only ancedotal knowledge of how its natives were destroyed! Sufficient data exist to indict nonnative fishes as a major part of the problem, yet stocking and spread of additional exotic species occurs and is proposed each year.

As a case in point, the striped bass, stocked as a game fish in the late 1960s in Lake Mead, proved too voracious a piscivore even for other nonnative species. At first, they appeared a tremendous success. Anglers, stimulated by the presence of "trophy" fish that are readily caught, swarmed to catch them. Entrepreneurs developed facilities and products to catch the angler's money. Management agencies also reaped a bountiful harvest—in funding for studies, public license fees, and goodwill so long as large fish were present, and strong criticism when the fishery collapsed. They were not expected to reproduce but did so prolifically, soon to overpopulate the reservoir. Available forage fishes, mostly threadfin shad, were unable to sustain the population. Large bass starved and died, and recruits persisted by shifting to smaller, inadequate food sources such as crayfish and zooplankton. This sequence of events was repeated in Lake Powell and now is happening in Lake Mohave, so regional management agencies have had ample opportunity and time to experience the repercussions of this management catastrophe.

Instead of absorbing their losses and seeking ways to reduce the striped bass population or use it most efficiently in its less than trophy state, a proposal now exists to stock rainbow smelt in Lake Powell, to augment food supplies (Gustaveson et al., 1990). The smelt, another predatory species, is expected to spread downstream through Marble/Grand canyons to Lake Mead and below. Proponents consider the smelt a potential salvation for striped bass fisheries of lower Colorado River basin reservoirs. I am of the opinion that if stocked and established, the species will be detrimental to both native and nonnative fishes throughout the system. I seriously doubt that smelt can sustain themselves in the face of striped bass predation, and certainly not for long at a level required to maintain large individual bass. I predict that they will reproduce and persist in low numbers in reservoirs, as do threadfin shad. There also is a good chance they will become locally abundant where safe from bass predation, notably in creek mouths and other quiet places other than reservoirs for which they are intended. In such places, the smelt will compete with and eat other desirable fishes. Introductions such as this, which will further damage fishes already clearly in jeopardy, must be prohibited.

Last, and most important in the real world, is the realization that agencies mandated to perpetuate endangered fishes may not act soon enough to save the native fauna of the Colorado River. Politics of the 1990s may not allow them to do so. The "good years" immediately following endangered species legislation in the 1960s and 1970s are over. In that period, agencies were responsive and even eager to participate in conservation of imperiled species and their habitats. Today, and for much of the 1980s, conservation issues have fallen by the wayside (Deacon and Minckley, 1991). Intransigence has become a major problem, albeit often masked by the "need" for interpretation of legislation and decisions regarding agency policy. Intransigence is deadly serious and unacceptable when dealing with extinction. Agency administrators must further avoid discretionary decisions not to implement programs or otherwise support recovery of a species because of other considerations; to do so is an abrogation of responsibility (Williams and Deacon, 1991). The public must demand through their governmental representatives that these issues be reemphasized. The task of conservation is primary, a responsibility to which other priorities should be subjugated. Species are not renewable resources.

CONCLUSION

The prognosis for native fishes in the Colorado River basin is poor. Water development is proceeding apace, and conservation efforts are caught in a whirlpool of development-related rationalizations. Even a complex Recovery Implementation Program for fishes in the upper Colorado River basin allows some water developments to proceed so long as a one-time fee is applied to recovery efforts (U.S. Fish and Wildlife Service, 1987; Wydoski and Hamill, 1991). The program funds research, purchases water rights for assurance of instream flow, and even examines curtailment of stocking of nonnative fishes that may harm natives, but it neither addresses definition of recovery (a common failing of most programs) nor provides assurances of alternative actions if the fishes have not benefited at the end of the designated program period (15 Years). As pointed out by Deacon and Minckley (1991), developments will be in place and operating, but the fishes may be extinct. When two organisms compete for a scarce resource such as water, the disadvantaged species seldom prevails.

The biologists have done their jobs. We know the life cycles and habitat requirements of endangered western fishes. Studies of their genetics, behavior, and reproduction are completed or in progress. In most instances, as problems arise, technology is such that solutions have been found prior to loss of species. Broodstocks of all of the larger fishes are already available, reintroduction programs are under way in parts of the Colorado River basin (Johnson and Jensen, 1991), and I am convinced that a successful management program could be devised and implemented for the Grand Canyon region. Current politics stand in the way, just as surely as politics of the

1960s aided and abetted our efforts to learn enough to save this fauna. We must have a renewed commitment by agencies and individuals. It is time for administrators to use available knowledge and expertise to fulfill their obligations, both ethically and under the law.

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APPENDIX I

Accounts of Species

Humpback Chub

Humpback chubs are restricted to the largest rivers and lower parts of major tributaries of the Colorado River system. In the mainstream, adults characterize whitewater reaches, where they occupy deep, swirling eddies along canyon walls or concentrate in zones of turbulence near boulders and other obstructions. In the Little Colorado River they live in deep pools near rapids and eddies, typically concentrating near cover such as overhanging ledges. Young have been taken in habitats similar to those of adults, from creek mouths, or from flatwater downstream from canyons.

The special morphologies of Colorado River fishes are combined in adult humpback chubs to form the most unique physiognomy of any North American minnow. Its most bizarre feature is a predorsal hump, rising in extreme individuals from the nape to extend anteriorly over the back of the skull (Figure 7-1). The hump is of muscle, connected through a wedge-shaped caudal peduncle to the large, stiff caudal fin. All fins are expansive and thickened anteriorly. The body appears almost naked, since the scales are small and deeply embedded. The eyes are small, the snout is bulbous and fleshy and overhangs the mouth. As with many Colorado River fishes, humpbacks can grow in 2 or 3 years to a relatively large size (~30 cm long) and then slowly over a life span of 20+ years (unpublished data) to a maximum length of more than 50 cm. Some tagged adults recaptured up to 8 years later had increased in length by only a few millimeters per year (Minckley, 1988).

Prior to formation of Lake Powell, humpbacks must have inhabited most of the river in Marble/Grand canyons and ranged upstream into turbulent parts of Glen Canyon. As determined from archaeological remains (Miller, 1955), they also lived in canyons downstream from Lake Mead. The only reproducing population in the lower basin is in the lowermost Little Colorado River (U.S. Fish and Wildlife Service, 1989b; Kubly, 1990). The few fish taken in Marble/Grand canyons presumably originate from the Little Colorado River stock (Kaeding and Zimmerman, 1982, 1983; Maddux et al., 1987). Other populations persist in the Yampa and Green rivers, upper Colorado River, and Cataract Canyon below the confluence of the Green and Colorado rivers (Tyus and Karp, 1989; Valdez, 1990).

The absence of reproducing humpback chubs in the lower mainstream is a function of water temperature. Natural river temperatures varied freezing in winter to ~30°C in summer. Hypolimnetic water from Lake Powell now enters the reach at 7.0–10°C. Volume of flow is such that even in summer it rarely warms to 16°C by the time it enters Lake Mead, more than 400 km downstream (Cole and Kubly, 1976; Kubly and Cole, 1979). The same pattern of avoidance of cold hypolimnetic water by native fishes was well documented below Flaming Gorge Dam (Vanicek et al., 1970; Holden and Stalnaker, 1975). Only a few North American cyprinids reproduce at such low temperatures (G. R. Smith, 1981), and no Colorado River species is known to do so, with the possible exception of the speckled dace (in part Marsh, 1985). Successful development and hatching of humpback chub eggs require 15°C or higher, and natural reproduction most likely occurs between 19 and 22°C (Hamman, 1982a, b; Kaeding and Zimmerman, 1983).

The Little Colorado River maintains much of its natural character despite upstream development (Miller, 1961). Snowmelt produces floods. The rest of the year, collective inputs of springs in its lower 21 km maintain a baseflow of ~5.6 $m^3 s^{-1}$, punctuated by infrequent runoff. Above its mouth, the stream flows in runs, rapids, and pools through a deep, narrow canyon. Travertine deposits from carbonate-rich springs are dominant features, forming scalloped cascades as well as a major waterfall 5.0 m high ~15 km upstream. At baseflow, the stream runs clear but milky in appearance as a result of suspended carbonates. Spring waters are also high in sodium chloride, with total salinities varying to more than 3.0 g $liter^{-1}$ (Cooley et al., 1969; Kubly and Cole, 1979).

The mouth of the Little Colorado fluctuates in depth and character as water releases from Glen Canyon Dam pass through the Colorado River mainstream. At low release rates, the Little Colorado enters the mainstream through a swift chute ~40 m wide. At high releases in the Colorado River, the mouth is ponded upstream for 0.5 km and varies from 1.0 to more than 3.0 m deep (Minckley, 1988).

Humpback chubs have consistently been the most abundant fish caught in the Little Colorado River over 14 years of sampling. When temperatures are similar in the two streams, chubs either move into the Colorado (Minckley et al., 1981) or swim back and forth between rivers. They move into the warmer Little Colorado in spring and summer, staging and spawning in the mouth, with some also moving upstream to spawn (Kaeding and Zimmerman, 1983; C. O. Minckley, 1988, 1989). Population sizes vary over the reproductive season (Kubly, 1990), indicating considerable movement of fish both within the Little Colorado River and between it and the Colorado River. Quantitative estimates of adults in spring, generated from tag-recapture data in 1980–1981 (Kaeding and Zimmerman, 1982) and in the period 1987–1989 (C. O. Minckley, 1988, 1989), respectively indicated 7,000–8,000, 5,783, 7,060, and 10,120 fish.

Other native species in the Little Colorado River include speckled dace and flannelmouth, bluehead, and razorback suckers, in decreasing order of abundance. Squawfish and bonytail were reported in the past below Grand Falls, 120 km upstream from the mouth (Miller, 1963b). Numerous alien fishes are found, but none abundantly. Fathead minnows, channel catfish, and carp are the most consistent in occurrence, and all three reproduce there. Perhaps salinity, carbonate deposition, floods, or some other special feature(s) precludes large populations.

Food habits of humpback chubs have not been thoroughly studied. Kaeding and Zimmerman (1983) reported mostly aquatic invertebrates in 27 fish that contained foods; one had eaten a fathead minnow. Three juveniles examined by C. O. Minckley (1980; Minckley et al., 1981) had eaten aquatic invertebrates and algae. Some adults from the mouth of the Little Colorado defecated or had their guts filled with the macroalga *Cladophora glomerata*, which indicated recent ingress from the adjacent mainstream where the alga was common (Minckley, 1988). Kubly (1990) also noted filamentous algae in 12 adults that contained foods; an unidentified fish was found, along with chironomid dipteran larvae and terrestrial insects. A few chubs caught below Glen Canyon Dam in the 1960s were filled with zooplankton (Minckley, 1973), and Tyus and Minckley (1988) recorded extensive feeding on crickets floating on the surface and used as bait in the Yampa River.

Bonytail

The ecology of the bonytail is poorly understood for a number of reasons. First, the vernacular "bonytail" was applied for years to any Colorado River basin chub of the genus *Gila*; therefore, older literature may or may not be usable. Second, it was long considered a subspecies of roundtail chub, and some workers combined the two kinds. Third, young chubs may be difficult to identify and are often lumped as "*Gila* spp.," or the rare species is simply ignored or missed in sorting. Next, apparent hybridization between chubs and questions of genetic integrity (Holden and Stalnaker, 1970; Valdez and Clemmer, 1982; Kaeding et al., 1986; Douglas et al., 1989; U.S. Fish and Wildlife Service, 1989b, c) have confused the issue even more. Last, bonytail are now too rare to study in nature (U.S. Fish and Wildlife Service, 1989c). While all this has gone on, the species declined in abundance to become the most endangered freshwater fish in North America. It now persists almost exclusively under artificial conditions (Minckley, 1985; Minckley et al., 1989).

Adult bonytails carry streamlining to different extremes than do humpback chubs. They are slim and elongate, with small, depressed skulls that rise smoothly to low, predorsal humps. The dorsal profile descends posteriorly to an attenuate, pencil-thin caudal peduncle, ending in a large, strong, deeply forked caudal fin (Figure 7-2). Its skin is thick, with deeply embedded scales. The body and fins are reminiscent of a pelagic member of the mid-oceanic community, e.g., a mackerel or tuna characterized by powerful and sustained swimming yet capable of sudden bursts of speed to attack prey or avoid a predator. In Lake Mohave, the last place wild bonytails may be predictably collected, they are often netted in midwater over shoals 5.0 to 10 m deep and seem to seek areas a few tens of meters from wave-washed shorelines during storms.

My best reconstruction of the natural habitat of bonytail is based on impressions from older literature, experience with formerly occupied habitats, and watching captives. The only direct observations known to me were those of Jonez and Sumner (1954), who "observed [it] in the sandy areas along the Colorado River." I suspect that the fish characterized valley reaches and perhaps flatwaters in canyons. Adult bonytail must have lived in mid-channel, maintaining position with low-amplitude beats of the caudal fin as they do in hatchery raceways, and moving from midwater to surface and bottom to inspect and feed on drifting particles in the water column. The potential power indicated by morphology would have been used to pass through zones of turbulence or escape predators.

One adult caught and preserved near Bright Angel Creek in the 1940s (Miller, 1946a) and skeletal material from Stanton's Cave (Miller and Smith, 1984) document bonytail presence in Marble/Grand canyons. Adults were often taken along with humpbacks, roundtail chubs, and putative hybrids between Lees Ferry and Glen Canyon Dam, and in Lake Powell, for a few years following closure of the dam (Stone, 1965–1969, 1971, 1972; Stone and Rathbun, 1967–1969; Holden and Stalnaker, 1970). Bonytalls were common in downstream reaches now inundated by reservoirs (Dill, 1944; Jonez et al., 1951; Wallis, 1951). Jonez and Sumner (1954) observed small schools (rarely more than 10 fish) scattered throughout Lake Mead in 1951–1954. All were longer than 25 cm, and no reproduction was seen although ripe females 30–36 cm long were observed along shorelines in March. They also saw breeding adults, apparent spawning aggregations, and actual spawning by at least 500 adults in Lake Mohave in May; 42 males and 21 females netted were 28–36 cm long. Spawning was observed with the aid of diving gear over a gravel shelf ~400 m long (Jonez and Sumner, 1954, p. 141–142):

> It appeared that each female had three to five male escorts. Neither males nor females dug nests, and the eggs were broadcast on the gravel shelf . . . . No effort was made to protect the eggs by covering them with gravel or by guarding them. However, the eggs adhered to the rocks, and that gave them some protection . . . . The bonytails found in the spawning area had bright reddish-gold sides and bellies. This color is not seen . . . at other times of the year; it is assumed that it is the spawning coloration. Bonytails from the swift-moving upper portion of Lake Mohave, although they were not observed spawning, occasionally were seen in like coloration in the spring of the year . . . . Large schools of adult carp were intermingling with the spawning bonytail. No young . . . were observed in the spawning area, and it is presumed that there will be enough survival . . . so that the bonytail will not become extinct in Lake Mohave.

As already noted, the Lake Mohave population persists today, with only limited recruitment (Minckley et al., 1989).

The few available data indicate that bonytails feed on benthic and drifting aquatic invertebrates and terrestrial insects (Kirsch, 1889; Vanicek, 1967). Jonez and Sumner (1954) reported plankton, algae, insects, and organic debris eaten in Lake Mead, and stomachs of adults from lakes Mohave and Havasu contained zooplankton (Minckley, 1973).

Like humpback chubs, bonytail grow quickly to large sizes. Some grow longer than 30 cm in their first year of life in artificial ponds (P. C. Marsh, unpublished data). Most wild fish captured from Lake Mohave vary between 45 and 55 cm in total length, and their estimated ages average near 40 years (Minckley et al., 1989). The largest individual known to me was caught in 1969 from the Colorado River below Davis Dam (unpublished data). It was ~64 cm long, estimated from other objects of known size in a photograph obtained by Gary Edwards (then with Arizona Game and Fish Department).

Colorado Squawfish

This giant minnow once achieved lengths of 1.8 m and weights of 36 kg. It was most commonly caught during the spring-summer spawning migra tion and staging of adults on and near the spawning grounds. Concentrations in canals and downstream from lower basin diversions before 1915 commonly included individuals up to 20 kg in weight; they and other native fishes were used as food for humans and domestic pigs and as fertilizer (Miller, 1961; Minckley, 1965, 1973).

Adult squawfish (Figure 7-3) are elongate and torpedo shaped, with long, flat heads, large mouths, and strong jaws. Large adults become markedly broadened across the back, reflecting their thick and powerful musculature. The caudal peduncle is stocky and short. The fins are relatively small, with the exception of a strong, expanded caudal, and the dorsal and pelvic fins are far back on the body. The scales are small and embedded, especially on the breast and belly, and the eyes are small. Young squawfish are more delicate in appearance, although clearly streamlined.

There are far fewer squawfish today than in the past. Miller (1961), Minckley (1965, 1973, 1985), and Minckley and Deacon (1968) documented their extirpation, mostly before 1970, from the Colorado River basin downstream from Grand Canyon. One preserved specimen is known from near Lees Ferry in 1934 (University of Michigan number 117840), and another, from the mouth of Havasu Creek (Arizona State University number 7087), was caught by an angler in 1975 (Smith et al., 1979). Both are juveniles less than 40 cm long. Skeletal remains from Stanton's Cave were of fish between 1.2 and 1.5 m long (Miller and Smith, 1984). A verbal report exists for squawfish in the Little Colorado River at Grand Falls (Miller, 1963b), and the species still lives in Lake Powell and in variable abundance upstream (U.S. Fish and Wildlife Service, 1989d).

Colorado squawfish have been studied in the upper Colorado basin for almost three decades. Using various methods, Tyus (1991) estimated-8,000 adults in the upper Green and Yampa rivers in the period 1980–1989. Absolute numbers are about an order of magnitude lower in the Colorado River above and below its junction with the Green (Valdez et al. 1982a,b; Valdez, 1990), and the fish is even more scarce in the San Juan River (Platania et al., in press).

Adult squawfish in the Green and Yampa rivers are solitary in relatively shallow, shoreline habitats, including shallow inlets and backwaters (Tyus and McAda, 1984). They occupy the same short reaches of river (~5.0 km long or less) from autumn through spring (Tyus, 1991). Spawning migrations begin with receding water levels in spring and early summer. Some fish move 200 km or more, passing through many kilometers of apparently suitable habitat to arrive at one of two widely separated spawning grounds by late June to early August. Colorado squawfish have shown unerring fidelity for one or the other spawning reach. The same fish used the same reach over a number of different years, and no fish changed from one to the other; olfactory homing was proposed to explain this behavior (Tyus, 1985).

On the spawning grounds, fish alternate between resting-staging areas in large pools or eddies and deposition-fertilization habitat on rapids. After spawning, adults return over a period of days or weeks to their previously occupied stream segments.

Squawfish eggs adhere to cobble and gravel of clean-swept bottoms, and larvae hatch in 3.5–6.0 days at 20–22°C (Hamman, 1981; Marsh, 1985). Temperatures at oviposition are typically higher than 18°C, and Marsh (1985) demonstrated dramatic reduction in hatching at temperatures less than 15°C. Under natural conditions, larvae emerge from the substrate in 3.0–15 days to move downstream. After a few weeks, the young concentrate 100 to 150 km below the spawning site in shallow, shoreline embayments formed as water levels recede through summer and autumn.

Little is known of the ecology of juveniles from ~10 to 30 cm long. Field data indicate the greatest numbers in lower sections of the Green River and more adults upstream (Tyus, 1986; Tyus et al., 1987). Partial separation of life stages may serve to reduce cannibalism (Tyus, 1991). Repopulation of upstream reaches must occur by subadults (Figure 7-4), 40–50 cm in total length.

Colorado squawfish grow more slowly than other native species. Rinne et al. (1986) reported growth to ~50 cm long in 9 years under hatchery conditions and speculated that a 1.8-m individual would be 50 or more years old or older. I suspect that estimate is conservative and would not be surprised if such a fish were 75 years old or older. Huge fish no longer occur, perhaps because of a high susceptibility to fishermen (Tyus, 1991). Growth rates of 59 tagged adults recaptured in the Green River averaged only 11.2 mm a year (Tyus, 1988). In 1981–1988, 14 ripe females caught on Green River spawning grounds averaged 65 cm long and 194 males averaged 56 cm long (Tyus and Karp, 1989). Examination of polished otoliths from wild Green River adults indicates ages of up to 30 years.

Small squawfish eat aquatic insects and crustaceans until they are 50–100 mm long and then shift to fishes (Vanicek, 1967; Vanicek and Kramer, 1969; Holden and Wick, 1982). Adults are piscivorous, lie-in-wait or slow-stalking predators, attacking in a rush that ends in strong suction created by opening the cavernous mouth. Under pristine conditions they must have eaten suckers most frequently. Today they feed on introduced fishes as well, sometimes choking on the erected fin spines of channel catfish that they attempt to swallow (Pimental et al., 1985).

In 1979, I theorized that adult squawfish in the lower Colorado River basin lived on the vast and complex Colorado delta (Minckley, 1979), migrating upstream to canyons of the Colorado and Gila rivers to spawn. Now we know more of their ecology, and if the pattern in the lower Colorado/Gila was like that in the Green River, adults congregated from their individual home ranges along both watercourses and migrated to spawn in whitewater canyons. The broad, rich delta might well have been a major nursery area. However, striped mullet, entering the delta from the Gulf of California in remarkable numbers (Hendricks, 1961), may still have attracted adult squawfish. Size and diversity of the delta prior to the construction of dams (Sykes, 1937) could have provided ample space and food for adult and juvenile squawfish alike.

Whatever the case, squawfish migration and reproduction in the lower basin were much earlier in the year than upstream. Young-of-the year seined in mid-May in southern Arizona were 32 mm long (Sigler and Miller, 1963) fully 2 months before spawning even typically occurs in the upper Green River. Newspaper accounts to be detailed elsewhere (W. L. Minckley and D. E. Brown, unpublished data) track angler catches of "white salmon" from the Gila River in the late 1800s at the Colorado-Gila River confluence near Yuma in March, at Gila Bend (-160 km upstream) in March–April, at Gillespie Dam (220 km upstream) in March–April, and at Tempe (~300 km upstream) in April–May. It seems likely that this sequence of catches follows the upstream migration of fish to reproduce. Snowmelt often begins by early March in the Gila River basin and ends in May, and the spawning grounds were likely in the Salt River Canyon, another 50+ km upstream from Tempe, where "commercial numbers" of squawfish were reported in those days (Chamberlain, 1904; Minckley, 1965, 1973). Whitewater canyons upstream from valley reaches that to serve as nurseries were also present on the Verde and upper Gila rivers, and adult squawfish were in both those systems (Minckley, 1973).

I have no comparable data for the lower Colorado mainstem but expect that runs were later there than on the Gila. Spring floods at Yuma extended well into summer because of the vast distances from sources of water; therefore, the fish might have moved any time from March through July. Adults aggregating from the delta and lower river may well have traveled more up the Colorado River than up the smaller Gila; distances from the delta to whitewater were a bit shorter in the former. Broad valleys of the lower river, including the basins now flooded by Lake Mead, would also have supported adults that could have spawned in upstream or downstream canyons.

Speckled Dace

This small minnow is the most widespread freshwater fish west of the Rocky Mountains, ranging from southern Arizona and California to Canada in desert springs, creeks, rivers, and high mountain brooks and lakes. The ecological breadth of this species is paralleled by its diverse morphology. Numerous subspecies are described, others are yet undescribed, and some workers (e.g., Minckley et al., 1986) suggest that the taxon actually repre sents a complex of species. In the Grand Canyon region, a mainstream form that also moves in and out of tributary mouths is referred to *Rhinichtys osculus jarrowi* (Figure 7-5). Stocks in tributaries above barriers are morphologically differentiated but have not been identified to subspecies. The mainstream form has a terete body, with larger, longer, and more falcate fins, sharper snout, longer head, and body pigmentation consisting of dark, longitudinal stripes or a uniform brown dorsum contrasting with a white belly. Distinctive tributary populations tend to have robust bodies with small, rounded fins, short, blunt snouts and head, and strong black speckles over-lying an olive ground color on the upper body. Speckles or blotches sometimes extend onto the venter. Breeding males of all the forms develop intense red pigmentation on the lower head, bases of fins, belly, and lateral body surfaces. Reproductive females remain drab or have yellow or orange pigmentation on the bases of ventral fins.

Speckled dace remain locally common in the channel upstream from Lake Mead, especially in creek mouths (Minckley and Blinn, 1976; Minckley, 1978; Carothers and Minckley, 1981). Large numbers can also be seined along sandbars in the river, but their actual abundance in that habitat has not been adequately assessed. They enter tributaries in March and spawn in April and May. Carothers and Minckley (1981) thought that reproduction was limited to tributaries at temperatures of 17 to 23°C. Young fish are common by late May and June. Both young and adults remain in lower parts of creeks throughout the summer and autumn, only to disappear into the mainstream in winter. Minckley (1978) attributed this winter exodus to interference by spawning aggregations of trout, but it also seems possible that winter river temperatures as warm as in tributaries make the mainstream more acceptable at that time of year.

Speckled dace achieve adulthood in a year or less. They rarely exceed 80–100 mm in length, and they live 2 or 3 years (Minckley, 1973). Foods in both mainstream and tributary habitats are mostly benthic invertebrates and organic debris (Carothers and Minckley, 1981).

Ubiquity of the speckled dace spells danger, especially if it indeed represents a complex of species rather than a single, variable, and widespread taxon. Commenness breeds complacency (or contempt), and most studies targeting a threatened or endangered species ignore other the other local fauna. At an extreme, significant numbers of streams have been poisoned for management toward recovery of endemic trouts (and even a few minnows), but associated native species have suffered as a result (Rinne and Turner, 1991). The trout is reintroduced after its habitat is renovated, but other warmwater, nontarget species are not. Speckled dace often bear the brunt of such a practice, and although we do not know what may currently exist with regard to this native species, we too often seem glibly prepared to allow the unexplored to vanish.

Flannelmouth Sucker

This is another species that persists in Marble/Grand canyons and throughout much of the upper Colorado River basin. It also occupies the Virgin River, Nevada-Arizona-Utah, which flows into Lake Mead. The flannelmouth sucker was described from the Gila River drainage of southern Arizona and also lived in the lower Colorado River near Yuma. It is now extirpated below Lake Mead (Minckley, 1985). W. L. Minckley (1980) examined flannelmouth populations in the Grand Canyon region, concluding that morphological variation was greater than to be expected in a single species. A related, undescribed form lives in the Little Colorado River (Minckley, 1973, 1980).

This complex has only a few special features of body shape. Their bodies are thick anteriorly and slim posteriorly. The anterior scales are small and embedded in thick skin. The fins are large, and the caudal peduncle is relatively thin. Nonbreeding fish are light gray or tan dorsally and white on the belly (Figure 7-6). Breeders are dark, with orange pigment on the fins and sometimes in a weak lateral band. Some adults exceed a length of 60 cm. Sexual maturity occurs at ~40 cm in the Yampa River (McAda and Wydoski, 1985).

Adult flannelmouths often lie in quiet tributary mouths, especially in the Paria River near Lees Ferry when the adjacent river is cold. Spawning was recorded by Carothers and Minckley (1981) in most larger, lower gradient stream mouths along Marble/Grand canyons. Ripe fish were caught in March to May in the Paria River at water temperatures of 17–23°C, and postreproductive fish remained there through the summer. As noted for other natives, adult flannelmouths left the Paria when its temperatures and that of the mainstream Colorado equilibrated in winter (Suttkus and Clemmer, 1979).

In the Yampa River, ripe adults appear from April through early June. They concentrate at the upstream ends of cobble bars in water 1.0 m deep and at velocities of ~1.0 m s^{-1} (McAda and Wydoski, 1985); abundant young, 30–40 mm long, are present by midsummer. Postreproductive adults remain in flatwater or eddies and margins of strong currents, generally in water 1 m or more deep. Young congregate on and downstream from riffles and along shorelines of flatwater reaches and in tributaries.

Gut contents of adult flannelmouths were similar in mainstream and tributaries of Marble/Grand canyons and included aquatic invertebrates, organic debris, and sand (the last reflecting bottom-feeding habits). Most invertebrates were larvae of aquatic dipterans, along with an introduced amphipod crustacean now common in the channel. Mainstream flannelmouths also commonly ate *Cladophora glomerata*. The alga was scarcely present in fish from tributaries (Carothers and Minckley, 1981).

The maximum estimated age based on growth rings on scales of upper basin fish was eight or nine years (Wiltzius, 1976; McAda, 1977; McAda and Wydoski, 1985). The scale method was rejected for large suckers in Marble/ Grand canyons by Usher et al. (1980) because a high percentage of the structures were regenerated and unreadable. The method has also proven unreliable for large razorback suckers in the lower basin. Minckley (1983) and McCarthy and Minckley (1987) reported that presumed annuli were obscure or too near one another to allow reliable separation after the first few years, and did not form at all in some years, all resulting in age under-estimation. Usher et al. (1980) and Carothers and Minckley (1981) concluded from opercular bones that the fish lived to a maximum of 10 years, which I also judge to be an underestimate. At the time of their study, neither the potential for long life nor the exceedingly slow growth now known for older Colorado River fishes was suspected. Thus, closely spaced annuli near the opercular margins may have been overlooked or misread. Scoppettone (1988) examined opercles from 30 Green River flannelmouths, the oldest of which was 30 years old and 53 cm long. Five sets of polished otoliths that I examined from Green River flannelmouths 50–59 cm in total length all were older than 17 years (unpublished data; the oldest fish was ~35 years old and 59 cm long). By any method of determination, it is clear that flannelmouths grow quickly in the first 3–5 years of life and then slow abruptly.

Bluehead Sucker

This is one of a group of specialized, mostly herbivorous fishes distributed in high-gradient streams of western North America (Miller, 1959; Minckley et al., 1986). Smith (1966) placed them as the subgenus *Pantosteus* of *Catostomus*, while Minckley (1973) retained full generic status for the group. Their feeding adaptations include broad, disc-shaped lips and strong cartilaginous sheaths on the jaws, used for grazing films of algae and other organisms.

There are few records of bluehead suckers downstream from Grand Canyon. Miller (1952) reported them as bait along the lower river, and some perhaps from that source were netted from reservoirs by Jonez and Sumner (1954). Perhaps the species was excluded downstream by the predominance of shifting sand bottoms. The Virgin River, tributary to the Colorado before being isolated by Lake Mead, is inhabited by a different species (Smith, 1966; Minckley et al., 1986).

Bluehead suckers in large rivers grow to ~50 cm long. They are bottom dwellers, with heads and bodies rounded above and flattened below, expansive fins, and thick skins. They have small, embedded scales on the anterior body and tiny eyes. The most remarkable feature of mainstream blueheads is their caudal peduncles, which vary among individuals from elongate and thin like that of a bonytail to short and thick like that of the Colorado squawfish (Figure 7-7). Specimens with intermediate peduncles also occur. The significance of this remarkable polymorphism, and its maintenance where extremes co-occur, are yet to be explained. Populations in the Little Colorado River are morphologically distinct (Minckley, 1973), with thick, chubby bodies, small rounded fins, and body lengths rarely exceeding 20 cm.

Nonbreeding, mainstream adults are bluish gray or olivaceous in color, with white bellies. The common name comes from breeding colors of adult males, which develop a blue patch on the top of the head that sometimes suffuses downward over the opercles. The lower fins become yellow or orange, and red or rosy lateral bands form along the sides.

When the water is clear, adult blueheads stay in deep pools and eddies in daytime, moving to shallow riffles, along shore, or to other hard-bottomed places to feed at night. When turbidity is high, they occupy shallow places throughout the day. Bluehead suckers seem most common at the upper ends of valleys or where shallows are available in whitewater canyons, but they tend to be rare elsewhere. Young are on and downstream from riffles and along shore in flatwaters. Like other natives, blueheads entered tributaries of Marble/Grand canyons in spring through autumn but were rare in winter.

Despite adaptations for scraping algae, foods of bluehead suckers in Marble/ Grand canyons were mostly immature dipterans and amphipods in the mainstream and dipterans in tributaries (Carothers and Minckley, 1981). Diatoms and organic debris were nonetheless abundant in guts at all seasons.

The same comments as before apply to reported ages of this species; the 8.0-year maximum age for Marble/Grand canyons fish reported by Usher et al. (1980) (Carothers and Minckley, 1981) may have been underestimated. Scoppettone (1988) used opercles to determine the age of a 40-cm specimen from the Green River at 20 years, while I (unpublished data) used otoliths estimate an age of greater than 20 years for an unusually large bluehead sucker (47 cm long) from the Yampa River. Growth rates of blueheads in the upper basin are rapid in the first few years of life, only to slow abruptly when sexual maturity is attained at 30+ cm total length (Wiltzius, 1976; McAda, 1977; McAda and Wydoski, 1983).

Blueheads spawn over mixed gravel-sand or gravel-cobble bottoms in moving water of tributaries in the Grand Canyon region, typically in April and May. Water depths vary from a few centimeters to deeper than a meter, and temperatures are typically 16 and often 20°C. A single female is joined by two to five males, and gametes are deposited on and within the bottom (Suttkus and Clemmer, 1979; Maddux and Kepner, 1988). Young appear in May and June. In the upper basin, they spawn over gravel and rubble, sometimes in very swift currents (faster than 1.0 m s^{-1}) near the upper ends of riffles, and mostly in flatwater reaches.

Razorback Sucker

Minckley et al. (1991) reviewed the biology of the razorback sucker, presented details on its current status, documented its decline, and reported on efforts for its recovery and management. Much of the following is abstracted from that work, which should be consulted for additional references.

This species, at maxima of ~75 cm long and 4.0+ kg in weight, is clearly the largest catostomid in the Colorado basin and second in size among all fishes to the Colorado squawfish. The razorback is named for a laterally compressed, sharp-edged keel rising abruptly from the nape and extending to the dorsal fin. The anterior body is thick and triangular in cross section (Figure 7-8), narrowing abruptly to the caudal fin. The skull is broad and flat to concave on the top and flattened on the bottom. While the relatively small mouths of most suckers extend ventrally when opened, the large mouth of the razorback can be protruded anteriorly. Razorbacks have tiny eyes, thick and leathery skins, small and embedded scales, and large, strong fins. Their dorsal and lateral musculature is thick and well developed, extending back through a robust caudal peduncle. Sexual dimorphism is pronounced. Males tend to have higher, sharper keels and larger fins, while females develop large, edematous urogenital papillae when breeding.

Razorback suckers are brown to brownish black on the back and yellowish on the belly (Figure 7-9), colors which darken and intensify during spawning. The dorsal body surfaces become suffused with dark red, concentrated laterally into a distinct lateral band. Young razorbacks are olivaceous to tan in color, and they resemble juvenile flannelmouth suckers until the keel develops when the fish is 80–100 mm in total length (Minckley and Gustafson, 1982).

This fish remains abundant only in Lake Mohave, Arizona-Nevada (~50,000 adults; Marsh and Minckley in press). It is rare or absent from the rest of the lower Colorado, and extirpated from the Gila River drainage prior to the 1960s. Razorbacks have essentially disappeared from Lake Mead, occur uncommonly in Lake Powell, and are also rare in the upper basin. An estimated 1000 razorback suckers persist in the upper Green River, the largest known concentration upstream from Lake Powell (Lanigan and Tyus, 1989).

One specimen from the Grand Canyon region was caught by an angler in 1944, Arizona Game and Fish Department personnel caught another near Lees Ferry in 1963, four were captured or seen in the Paria River in 1978–1979 (Minckley and Carothers, 1980), one was taken in the mainstream in 1986, three were seen in 1987 in Bright Angel Creek, and two and three, respectively, were netted in the mouth of the Little Colorado River in 1989 and 1990. Putative hybrid razorback × flannelmouth suckers have also been recorded (Suttkus and Clemmer, 1979; Carothers and Minckley, 1981). Considering the size and complexity of the 400+ km of river in Marble/ Grand canyons, the number and diversity of tributaries, and the comparatively limited sampling for such a massive habitat, records of 13 razorback suck ers since 1978 may indicate a significant remnant population. All were large adults, but all known populations consist of large, old fish. No recruitment is indicated for any wild population for more than 20 years.

In the upper basin, razorback suckers spawn near the upstream ends of gravel-cobble riffles during May and early June, at water temperature higher than 16°C and velocities less than 1.0 m s^{-1}, and generally in places less than I in deep (McAda and Wydoski, 1980; Tyus, 1987). Turbidities are too high for direct spawning observations in the Green River, but in clear water in the short reach of river below Lake Mead, two or more males accosted each female entering a spawning area (Mueller, 1989). Eggs were deposited in depressions formed by movements of the large fish against the bottom. The ecology of juveniles, only a few of which have ever been collected, is unknown.

For years after impoundment, hundreds of breeding razorbacks aggregated over wave-washed, gravel-cobble bottoms along shorelines in lakes Mead, Mohave, and Havasu (Wallis, 1951; Douglas, 1952; Jonez and Sumner, 1954). There is evidence of the same phenomenon in reservoirs on the Salt River, Arizona, before the 1950s (Hubbs and Miller, 1953; Minckley, 1983). These fish were either trapped by the dams or, most likely, originated from high production and survival of young before populations of exotic fishes exploded in the newly formed lakes. Based on paleo-Indian fishing wiers and other indirect evidence, razorbacks did the same thing in the Salton Sea when it was periodically filled from Colorado River floods in the distant past (Minckley et al., 1991).

Razorback suckers have consistently disappeared from lower basin reservoirs 40–50 years after impoundment (Minckley, 1983). As already noted, only Lake Mohave, formed by Davis Dam in 1954, now supports the species. If otolith aging is correct (McCarthy and Minckley, 1987), Lake Mohave fish averaged ~35 years old in 1980–1981. Most hatched about the time the lake was formed and thus may have only 5.0–15 years of longevity to go. It is notable in this regard that 10 Green River razorbacks taken downriver from Flaming Gorge Dam mostly after 1980, averaged ~29 years old (W. L. Minckley, 1989); that reservoir was closed in 1963.

Razorback spawning in Lake Mohave is most intense in late January through early April at temperatures higher than 15°C. Larvae emerge in a few days, move inshore, develop to ~12 mm long, and then disappear. Despite production of strong larval year classes, no recruits to the adult population have been discovered in sampling since 1967.

Three hypotheses have been proposed to explain the larval disappearance: (1) starvation, (2) entrainment and transport from the reservoir, and (3) predation by nonnative fishes. The last seems most parsimonious. After removal of nonnative predators by rotenone, adults placed in a backwater isolated from the lake by a gravel spit reproduced naturally, and young fish grew to 25 cm long or more in less than a year. The species also reproduces successfully, and young grow rapidly to large size in hatchery or other artificial ponds so long as predatory exotics are denied access (Minckley et al., 1991).

Food habits of razorback suckers are poorly known. In reservoirs, both larvae and adults eat zooplankton, and the large, terminal mouths and specialized gill rakers seem adaptations for seiving suspended materials from the water column (Hubbs and Miller, 1953; Marsh, 1987). This characteristic fits if the species evolved in ancient lakes, which is possible although no fossils have been found in lacustrine sediments, or if they primarily inhabited backwaters and oxbows along the pristine river.

Another alternative lies in the probable efficiency of such an anatomical system for seiving detritus from the stream itself. As noted before, finely ground detritus must have been far more abundant in the past than is commonly realized. Razorbacks in the Green River channel apparently lie in depressions behind current-formed dunes on the bottom, where particulate organic material collects after elutriation from entrainment in the shifting, inorganic bottoms. This detritus is thus available as food, at least for a time until it is suspended and carried away or reinterred by ever-moving sand. Guts of razorbacks caught from rivers have usually contained large proportions of "organic matter," along with lesser amounts of aquatic invertebrates and considerable sand (Marsh, 1987; Minckley et al., 1991). Perhaps a large enough population to study, if ever found or reestablished, will provide tests for these speculations.

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8

Historic Changes in Vegetation Along the Colorado River in the Grand Canyon

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ABSTRACT: Glen Canyon Dam has irreversibly changed the Colorado River in Grand Canyon. Prior to the dam, sediments and associated nutrients were transported into the canyon from upstream, with a large percentage of those sediments and nutrients then flushed from the system as output, supporting downstream systems. These predam sediments and nutrients supported aquatic and terrestrial organisms of the river corridor throughout Grand Canyon. The dam has drastically reduced upstream input, making the Colorado River ecosystem in Grand Canyon more nearly a closed system. Downstream systems, e.g. the fishery in Lake Mead, have also been impacted by the loss of nutrients trapped in Lake Powell.

Both riparian and aquatic ecosystems have been impacted by postdam flow regimes. Prior to the construction of Glen Canyon Dam the components of the natural riverine ecosystem of the Colorado River in Grand Canyon were driven by high energy, pulsing events typical of southwestern rivers. Three pulsing features of the river affected by the dam included, in decreasing importance to the riparian ecosystem (1) seasonal flow patterns and maximum/minimum flows (2) nutrient and sediment transport and turbidity and (3) fluctuations in water temperature. Riparian vegetation was dependent on moisture, nutrients, and sediments supplied by the river. Flooding is a natural phenomenon in riparian habitats, thus riparian species are generally flood adapted. However, in the Grand Canyon predam high flows and sediments transported by those flows scoured vegetation from the riparian zone on a regular basis.

Riparian ecosystems are ecotonal, interfacing between the upland zone of the terrestrial environment and the adjacent aquatic environment of the river. As such, species richness and population densities both tend to be higher in riparian ecosystems than on adjacent uplands because of the edge effect. The term naturalized ecosystem has been used for the riparian ecosystem in Grand Canyon, an ecosystem in which native processes have not been appreciably interrupted and/or nonflative (exotic) species have become naturalized, causing no loss of native species. By contrast, the aquatic ecosystem in the Grand Canyon is an exotic ecosytem, an ecosystem that has been so extensively modified that it consists of a humanly created environment in which native processes have been interrupted, nonnative species abound, and native species have been extirpated.

Early investigators in the Southwest applied the concept of desertification to "water projects," notably reclamation projects and other river management activities. Desertification, leading to increasingly xeric conditions, has resulted in losses of 90% to 95% of the riparian habitat throughout the Southwest lowlands. By contrast, a more constant postdam water supply has resulted in the riparian environment in Grand Canyon becoming increasingly mesic. The Colorado River in Grand Canyon is the only major riverine ecosystem in the lowland Southwest where there has been an appreciable increase rather than a decrease in riparian vegetation and associated animal populations during the 1900s. The importance of riparian habitat to wildlife and humans has been extensively documented. The riparian zone in Grand Canyon is used extensively by whitewater recreationists, hikers, and a large number of native animals. Thus, the proper management of riparian vegetation in the canyon is of primary importance.

INTRODUCTION AND OBJECTIVES

The Grand Canyon, one of the original seven natural wonders of the world, is located in northern Arizona, on the Colorado Plateau Province, a region called by the noted geologist Hunt (1967) "easily the most colorful part of the United States." The canyon is of great interest to resource managers, recreationists, scientists, and politicians. At least two ex-presidential candidates have written about the canyon—Arizona Senator Barry Goldwater (1940) and former Governor Bruce Babbitt (1978). It serves as a textbook example for stratigraphic studies in its more than a billion years of exposed geologic history. Grand Canyon National Park receives more than three million visitors annually, approximately 22,000 travel down the Colorado River, considered by many to be the world's premiere whitewater river. Approximately 100, 000 additional recreationists use the river between Glen Canyon Dam and Lees Ferry, half as fishermen, the others on raft trips. The region's biological importance was assessed thusly by one of this century's greatest mammalogists (Hall, 1981), "Concerning subspeciation, which is a step toward the formation of species, the southwestern quarter of the United States. . .has a larger number of subspecies than any other continental area of equal size in the world. . .The reasons seem to be high degree of relief. . .deeply cut, steep, rock-walled canyons (the Grand Canyon of the Colorado, for one), resultant wide range in temperature, sharply marked zonation of plants, and tremendous diversity of types of soil." It is this environmental diversity, so important to both natural and cultural systems, and the impacts of water management systems on this diversity that we address here.

Glen Canyon Dam has irreversibly changed the Grand Canyon environment. Interactions between humans, vegetation, and flow levels are often complicated. Some plants and animals are adapting to postdam conditions (Carothers and Dolan, 1982), others are not. Some changes are local, e.g. the gradual downhill displacement of sand into the river as a result of camper's footsteps (Valentine and Dolan, 1979). Prior to construction of the dam, this lost sand would have been replaced almost on an annual basis by high spring flows. Other changes are large scale, impacting not only the riverine system within Grand Canyon but also affecting ecosystems hundreds of miles downstream. For example, the Colorado River formerly transported sediments and associated nutrients into the canyon from tens to hundreds of miles upstream. The dam has drastically reduced this input, making the Colorado River system in Grand Canyon more nearly a closed system. These predam sediments and nutrients supported aquatic and terrestrial organisms of the river corridor. A large percentage of those sediments and nutrients were flushed from the canyon as output, supporting downstream systems. Thus, the dam has also impacted systems further downstream, e.g., the fishery in Lake Mead that suffers from a loss of nutrients trapped in Lake Powell (Evans and Paulsen, 1983; and numerous other papers by Paulsen et al., *in* Adams and Lamarra, 1983).

The possible loss of integrity of the ecological fabric of the region, or even modification of critical features of the region, is of interest to us here as we evaluate vegetational changes, specifically changes in riparian vegetation along the Colorado River. Johnson and Carothers (1987) called the riparian ecosystem in the Grand Canyon a *naturalized ecosystem*. A naturalized ecosystem is one in which native processes have not been appreciably interrupted and/or nonnative (exotic) species have become naturalized, causing no loss of native species. Attempts to reconstruct lists of the predam biota during studies in the 1970s and 1980s have failed to demonstrate the loss of riparian species since the construction of Glen Canyon Dam in 1963. Instead, the addition of nonnative species along the river corridor has increased species richness within riparian biotic communites, apparently without the deleterious effects often associated with nonnative invaders. However, thirty years is an infinitesimal length of time in the evolution of natural communities such as those in the Grand Canyon. By contrast, the aquatic ecosystem in the Grand Canyon is an *exotic ecosystem*, an ecosystem that has been so extensively modified that it consists of a humanly created environment in which native processes have been interrupted, nonnative species abound, and native species have been extirpated.

Riparian ecosystems are ecotonal, interfacing between aquatic and terrestrial ecosystems. As such, species diversity and population densities both tend to be higher in riparian ecosystems than in adjacent upland ecosystems because of the edge effect (Johnson, 1979; Odum, 1979). The newly created riverine environment in the Grand Canyon consists of a series of subecotones, or subzones, even further expanding the edge effect and increasing biotic diversity and population densities. Since the terms subecotone and subzone are not in common usage, the riparian zone of the Colorado River in Grand Canyon has, by convention, been further divided into even smaller "zones." The terms Old High Water Zone and New High Water Zone are so widely used that they are commonly abbreviated OHWZ and NHWZ (and will be so designated throughout this paper). This loose use of terminology, or perhaps better, nonheirarchical use of a nontechnical term, zone, leads to confusion if one does not realize that the NHWZ and OWHZ are actually subcategories of the riparian "zone."

In examining the riparian ecosystem of the Colorado River in Grand Canyon, vegetational studies are critical. Plants making up riparian vegetation serve as processors of environmental conditions, biological computers if you wish. Unlike animals, plants cannot move from one location to another, thereby escaping changes from day to day or year to year. Therefore, they respond to changes in temperature, soil, moisture, slope, aspect, and the multitude of other climatic, edaphic, and related conditions of their environment. In turn, vegetation serves as a substratum for animal life, including humans—prehistorically serving a critical subsistence function, today a greatly sought after recreational function. Thus, vegetation is probably the best component for assessing the "health" or condition of the riparian segment of this riverine ecosystem. By correctly interpreting changes in vegetation over time we can thereby evaluate the past and present "health" of the ecosystem and postulate what is to come.

Objectives

Although our task here is the discussion of historic changes in riparian vegetation before the 1980s, projections for the future of species and processes along the river corridor necessitate some discussion of research during the 1980s, especially recent findings from the Glen Canyon Environmental Studies (GCES). Thus, in order to make our story complete, within space limits, we can stay neither entirely within that time period, the riparian zone, nor vegetation. Other essential areas of discussion include floristics since riparian vegetation of the river corridor is composed of individual plants of numerous species. And finally, a basic ecological principal, simply put, states that in nature everything is connected to everything else. This, then necessitates our addressing the interaction of plants with water and other components of the aquatic ecosystem as well as the interdependence of terrestrial animals, and to a lesser degree aquatic animals, on riparian vegetation.

HISTORY AND BACKGROUND OF BOTANICAL EXPLORATION ALONG THE COLORADO RIVER IN GRAND CANYON

The first humans cognizant of riparian vegetation along the Colorado River in Grand Canyon were prehistoric groups to which certain floristic components of the vegetation were of subsistence or ceremonial importance. Since these early canyon inhabitants left no written record we must rely on plant and animal lists from archeological excavations—for summaries see Fowler, et al. (1969), Euler (1984) and Jones (1986). Paleontological records provide additional biological information from riverside sites (for summaries see Euler, 1984) but most palaeoecological studies deal with upland vegetation, especially those analyzing fossilized plant remains from packrat middens (Cole, 1990). Thus, 3,000 to 4,000 year old split-twig figurines recently excavated from riverside Stanton's Cave (Euler, 1984) that had been made from obligate riparian willow and cottonwood are a good indication that those species grew along the river and/or its tributaries at that time. (Scientific names of plants in text are listed in Appendix A; animals are given parenthetically the first [and usually only] time the species is mentioned.) However, human proclivity for carrying things around and the movement of plant materials by wind and water make both paleontological and archeological analyses of limited value for our purposes.

It is difficult to extrapolate back in time from limited information, especially for determining changes in an area such as along the Colorado River in Grand Canyon, one of the most inaccessible regions of temperate North America. Unfortunately, we find extrapolation necessary not only for paleontological and archeological information but for much of the historic record as well, noted more for its gaps in information rather than for usable biological information. Checklists for the flora and fauna of the river corridor were incomplete until intensive surveys of the 1970s. For example, *Dicoria brandegei* ("Unknown Compositae #1" on my early 1970s collecting expeditions along the river) is a common and widespread native plant about the size of a small, nonnative Russian thistle. Dicoria commonly grows as a pioneer species on sandy deposits along with Russian thistle, especially along the upper reaches of the canyon. After being left from early plant lists for Grand Canyon, it was finally included in the latest checklist (Phillips et al., 1987) as "common on sand dunes along the Colorado River from CRM [Colorado River Mile] 38–232." The species was not listed by MacDougall (1947) in the Grand Canyon Natural History Association's third edition of the park plant checklist (first edition in 1932) nor by Clover and Jotter (1944). Since the species could hardly be overlooked it is presumably a post-dam invader, adapted to sandy deposits above the current normal high water mark, sites that were often scoured clean of fluvial sands, vegetation, and seeds by predam high flows. However, in addition to excluding dicoria, McDougall (1947) also excluded tamarisk from his checklist although Clover and Jotter (1944) had previously listed tamarisk as common at several localities. Although some botanical purists do not list nonnatives, e.g. tamarisk, McDougall listed numerous other nonnative species, e.g. clovers, sow thistle, etc., with annotations that they were exotics—so we are left with the uncertainty of an unsolvable mystery in relation to dicoria's establishment in the Grand Canyon.

PHOTOGRAPHY AND THE BOTANICAL RECORD

The first systematically collected vegetational information from the Grand Canyon was by photographers. Earlier explorers, e.g., Powell, commonly took notes on the geology and even Indians but little was mentioned in their journals about vegetation. The following information about photographic expeditions were taken largely from Graf (1978), Turner and Karpiscak (1980), and Stevens and Shoemaker (1987).

The earliest scientific records for the Colorado River in Grand Canyon were accompanied by thousands of photographs that have been recently used for a series of comparisons with more recent photos. The first of these were by the Powell Expeditions of 1869 and 1871–72, especially the second expedition. Later expeditions of the late 1800s and early 1900s included the Wheeler Expedition of 1871–73, the important Brown and Stanton Railway Survey of 1889–1890, and miscellaneous still photography discussed by aforementioned authors. Photographic records from the early 1900s include the first motion pictures by E.L. and E.C. Kolb in 1911. The U.S. Geological Survey (USGS) photographed potential damsites during the early 1920s and sponsored Stephens and Shoemaker's special expedition through the canyon in 1968 (Stephens and Shoemaker, 1987), one year before the Powell Centenniel, for comparing photos with those taken a century earlier by Powell's photographers. These photos show and occasionally mention vegetation but they were largely concerned with geology.

Although these numerous earlier expeditions had photographed vegetation along with the geology of the canyon the botanical value of most of these photos was generally limited and even the vegetation in these photos was not critically examined until the 1970s. Turner and Karpiscak's work in the 1970s, sponsored by the USGS and MNA (Museum of Northern Arizona) (Carothers and Aitchison, 1976; Turner and Karpiscak, 1980) is the most complete photo comparison of vegetation before the GCES of the 1980s. Thus, although photography was generally accomplished with little botanical intent, in retrospect much of this earlier photography has served a useful function for vegetational comparisons through time.

Recent Research and Plant Collections

The first systematic plant collections and floristic notes containing vegetational information was by Clover (1942) and Clover and Jotter (1941, 1944). The Clover and Jotter Scientific Expedition (or Nevills' Expedition of 1938) consisted of three cataract boats that left Lee's Ferry on July 12, 1938. In addition to being the first biologists to conduct research along the river Elzada Clover, 41 year-old botany professor from the University of Michigan and her young lab assistant, Lois Jotter, were the first women to travel through the Grand Canyon. At Phantom Ranch the expedition was joined by Emery Kolb, boatman and aforementioned motion picture photographer. The expedition reached Lake Mead, more than 250 miles downstream, in late July. Clover spent part of the following year collecting at localities along the canyon that she could reach by car or foot. Botanical specimens and information collected on those two trips constituted the only critical examination of the biology of the canyon until the 1970s. Even with the impending construction of Glen Canyon Dam in the 1950s and 1960s all biological "salvage" investigations were conducted upstream of the damsite in a riverine ecosystem that was to be inundated by Lake Powell (Woodbury, 1959). The possibility of large scale changes that were to occur in downstream aquatic and riparian ecosystems were not considered until they became obvious, after the completion of the dam.

In the late 1960s and early 1970s there was increasing interest in the biological, physicochemical, and socioeconomic parameters of the Colorado River in the Grand Canyon. There was much concern about the "carrying capacity" for campers on the alluvial terraces, or "beaches," along the river and interrelationships between campers, vegetation, and other components of the riverine environment (Dolan et al., 1977; Johnson et al., 1977). In response to these concerns research planning was instituted through the Grand Canyon Research Advisory Board, formed under the auspices of the Arizona Academy of Science in cooperation with the National Park Service (NPS). The board consisted of an interdisciplinary consortium of scientists, knowledgeable about the canyon, that advised NPS on research needs for the river. Beginning in 1970 a series of river expeditions was sponsored by this group and the Grand Canyon Natural History Association. Research expeditions varied somewhat in their basic missions, usually traveled by raft, and were composed of scientists from several different disciplines. Issues regarding recreational demands and environmental concerns, combined with a court case filed by river recreationists, eventually reached such a level that in July, 1973, the Washington, D.C. office of NPS funded a research trip through the canyon. A Colorado River craft (37 ft. pontoon raft) with two boatmen carried eight scientists and two assistants who spent 16 days on the river evaluating almost 400 campsites (Borden et al., 1975). For the larger campsites evaluations included physical characteristics and capacity (numbers of campers), shoreline (sand vs. rock, landing conditions, bathing conditions, etc.), vegetation, photography available and other factors.

Scientists involved in these earlier expeditions formed a core of research leaders that have contributed much of the information in this current paper, either in published papers, manuscripts, or by personal communication. By 1976, thirty projects and numerous river research expeditions had been funded by NPS under the Colorado River Research Program. The studies were coordinated from 1973 to 1976 by NPS Research Scientist R. Roy Johnson and the earliest riparian studies were conducted by a research team from the Museum of Northern Arizona under the leadership of Steven W. Carothers, Curator of Biology. NPS allocated more than 3/4 of a million dollars for studies and eighteen research reports published by NPS Western Region Office (Johnson, 1977). Also, during the 1970s and 1980s a great proliferation in publications for the Colorado River accompanied these research efforts. Numerous other reports and papers were published in other series and the open literature. Most publications through the 1970s were referenced in a bibliography (Spamer et al., 1981). In addition to referencing the more important summary and synthesis papers from that bibliography, throughout this paper we also reference works from throughout the 1980s that are most important to our discussions of vegetation (see also USDI, 1988).

DISCUSSION

Prior to the construction of Glen Canyon Dam the riparian and aquatic components of the natural riverine ecosystem of the Colorado River in Grand Canyon were driven by high energy, pulsing events typical of southwestern rivers. Three pulsing features of the river affected by the dam included, in decreasing importance to the riparian ecosystem (1) seasonal flow patterns and maximum/minimum flows (2) nutrient and sediment transport and turbidity and (3) fluctuations in water temperature (Carothers and Johnson, 1983). Riparian vegetation was dependent not only on moisture from the river but also on nutrients, and sediments carried by the river's water. Although fluvial sediments provided an ideal substratum for riparian vegetation, high flows and sediments transported by those flows also scoured vegetation from the riparian zone on a regular basis.

Increasing salinity of western rivers is one of our most serious problems (Pillsbury, 1981), not only from a standpoint of human usage but also because of its impacts on natural riverine ecosystems. However, little is known of salinity and other critical riverine issues in Grand Canyon. The roles of impoundments and associated evaporation and dissolution processes in increasing salinity of water and soil further downstream are well known (Paulson and Baker, 1983). However, total dissolved solids (TDS) have not increased appreciably in Grand Canyon and below Hoover Dam (Paulson and Baker, 1983) during recent monitoring. Presumably most of these salts have settled out in reservoirs above the dam but too little time has passed to evaluate long term effects. Paulson (1983) advocates the use of dams in controlling salinity in rivers. The interrelationships of riparian plants with soil and water salinity are being studied for our area by Stevens (ms and personal communication) who finds salt levels in soils of the newly established riparian zone along the river (NHWZ) of approximately 1/10 the level of predam fluvial terraces.

In addition to interrelationships between riparian and aquatic ecosystems the riparian zone is also closely linked to adjacent upland terrestrial ecosystems. Riparian ecosystems throughout the Southwest present a verdant ribbon of vegetation, contrasting sharply with more arid, upland landscapes. These cooler, more mesic environments are heavily utilized by hikers, whitewater recreationists, and wildlife. Riparian ecosystems of and regions are noted for their high recreational and wildlife values (Johnson and Carothers, 1982). The riparian zone along the Colorado River in Grand Canyon is no exception. The green of tamarisk, willows, seepwillows, mesquite and other riparian species often ends abruptly at the talus or desert uplands where it is replaced by browner and yellower hues of creosotebush, ocotillo, barrel cactus, numerous species of *Opuntia*, other cacti and other typical desertscrub species.

PREDAM AND POSTDAM VEGETATIONAL COMMUNITIES

Prior to construction of Glen Canyon Dam spring floods resulting largely from melting of headwater snow in the Rocky Mountains and Colorado Plateau attained an average high of 86,000 cubic feet per second (cfs) (2,430 cubic meters per second [cms]), but commonly exceeding 100,000 cfs (2,830 cms). At least one historic flood approximated 300,000 cfs (8,490 cms) at Lee's Ferry (Dolan et al. 1974). These floods, and the heavy silt load that had given the river its Spanish name, Rio Colorado (Colored or Red River), scoured vegetation from the rocky canyon sides and replaced sandy terraces and their vegetation with new, unvegetated sand. Woody riparian plants were provided with adequate water but generally grew above the scour zone at the OHWZ.

A few years after the completion of Glen Canyon Dam in 1963, a proliferation of woody riparian vegetation became apparent. However, this vegetation was situated lower on the Colorado's banks in the NHWZ, or post-dam fluvial sediments of Dolan et al. (1974). This new relationship between flow levels and vegetation regimes was first discussed by Dolan et al. (1974) and more recently by Johnson and Carothers (1982). Prevalent species of the OHWZ, or high predam flood terraces of Dolan et al. (1974) are shown in Figure 8-1.

CLASSIFICATION OF DESERTS AND PLANT COMMUNITIES

The upland vegetation of the Inner Gorge of the Grand Canyon consists of Great Basin Desertscrub and Mohave Desertscrub. This was discussed early by Bennett (1969), one of the first to examine postdam riparian plants. The river corridor was mapped as Great Basin Desertscrub from Lee's Ferry downstream to approximately 10 miles below the Little Colorado River and as Mohave Desertscrub from there downstream past the Grand Wash Cliffs (Brown and Lowe, 1980). Detailed maps of this riparian vegetation were prepared in 1977 by the Museum of Northern Arizona staff at a scale of 1:9600, with contour intervals of 200 feet (Table 8-1). The Grand Canyon region is best known in the natural community literature as the site used by C. Hart Merriam (1890) in formulation of his Life Zone concept. Riparian ecosystems from Lee's Ferry to Lake Mead all occur in the Upper and Lower Sonoran zones.

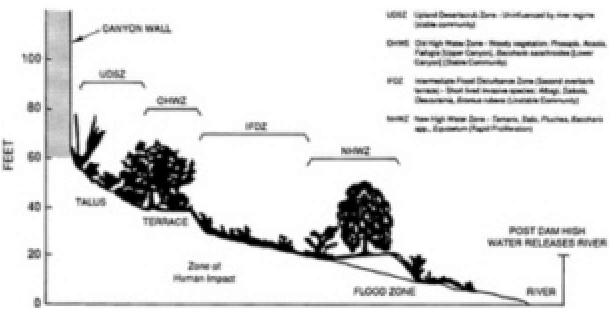

FIGURE 8-1
Profile of the vegetative zones of the Colorado River floodplain in the Grand Canyon prior to the construction of Glen Canyon Dam (after Johnson and Carothers, 1982).

TABLE 8-1 Vegetation types and common genera of the 1977 MNA-NPS map.

VEGETATION TYPE	COMMON GENERA
Winter-deciduous orthophyll forest	*Acer, Fraxinus, Salix*
Deciduous sclerophyll forest	*Tamarix*
Deciduous sclerophyll woodland	*sparse Tamarix*
Evergreen sclerophyll scrub	*Pluchea*
Deciduous orthophyll scrub	*Baccharis, Brickellia, Salix*
Microphyllous deciduous thorn scrub	*Acacia, Prosopis*
Closed deciduous scrub in scattered trees	*Fallugia, Cercis, Celtis*
Seasonal orthophyll marsh	*Epipactis, Mimulus*
Season sclerophyll marsh	*Phragmites, Typha*
Desert scrub	*Agave, Larrea*
Salt bush desert	*Atriplex*
Microphyllous deciduous desert scrub	*Acacia*
Seasonal & evergreen desert herb vegetation	*Abronia, Eriogonum*

Source: Museum of Northern Arizona, 1977. On file, CPSU/UA, NPS, Tucson.

Riparian plant communities are simpler than upland communities; that is, fewer riparian plant communities occur along a given elevational or geographic gradient than along the same gradient in adjacent upland communities. This is due, at least in part, to the greatly ameliorating affect of water in the adjacent stream course (Johnson and Haight, in press). However, microhabitats and associated niche availability to animals are generally greater in riparian environments, especially in and regions where more synusia (vegetational strata) are commonly present. Plants are also more closely spaced in riparian communities than in adjacent upland communities. Adequate moisture in riparian communities results in differing community dynamics from adjacent uplands where underground competition for moisture serves as a critical selection factor (Johnson et al., 1989).

Miller et al. (1982) added "Colorado River Beach," in dealing with amphibians and reptiles of the Grand Canyon. This was an additional riparian biotic community to Hoffmeister's (1971) "Riparian of Inner Gorge." Since riparian means, most simply, "streamside" (Johnson and Haight, in press), vegetation is not a requirement of a riparian environment and in the Grand Canyon much of the riparian zone consists of bare soil, rocks, or sand.

THE COLORADO RIVER AS AN EXCEPTION TO RIPARIAN DESERTIFICATION

The concept of desertification was originally applied to desert upland regions, usually in third world countries, notably Africa. Early investiga tors in the Southwest applied the concept to "water projects," i.e. reclamation projects and other river management activities that resulted in the degradation and destruction of these native riverine ecosystems (see Lowe, 1964; Phillips et al., 1964; Hastings and Turner, 1965). As desertification has become an increasing problem in riverine environments of the North American Southwest the term as well as the concept has become increasingly widespread in its application to these activities Books treating the issue in the southwest include Sheridan (1981), Dobyns (1981), and Rea (1983) as well as shorter papers. Johnson and Simpson (1988) and Johnson and Haight (in press) have defined desertification as "The human-driven process which interrupts natural processes, resulting in the physical, chemical and/or biological deterioration of water, soil and/or air resources. This effects a reduction in biological productivity, resulting in both a perceptual and actual reduction in the region's natural and cultural carrying capacity." Desertification results in increasingly xeric conditions. However, the riparian environment in the Grand Canyon has become increasingly mesic, especially at localities where postdam marshes support cattails, bulrushes, and other mesophytes and hydrophytes. This is largely due to two hydrological changes in postdam flows 1) cessation of scouring from silt-laden spring floods and 2) a relatively constant year-round water supply to riparian plants.

EARLY STUDIES AND IMPORTANCE OF RIPARIAN LANDS AS AVIAN HABITAT

Desertification has resulted in losses of 90% to 95% of riparian habitats throughout the Southwest lowlands (Johnson and Carothers, 1982). These are critical losses since these riparian-lands generally support five to ten times the numbers of individuals and several times the numbers of species compared to adjacent uplands. Some of the earliest riparian studies examined bird-plant relationships in the North American Southwest. The importance of these riparianlands to the nesting avifauna of the region was first documented in studies by Carothers et al. (1974a). These studies reported the highest population densities for noncoloial nesting birds for North America from along the Verde River in central Arizona. More recently, Johnson et al. (1977, 1987) have further discussed the importance of riparianlands to breeding birds of the Southwest lowlands. The heavy use of riparian habitat by migrating birds was addressed early by Stevens et al. (1977). Johnson and Haight (1985, 1988) documented the importance of riparianlands to wintering birds.

Since other riparian ecosystems throughout the Southwest have been so heavily depleted, riparian vegetation in the canyon is of great value. The riparian ecosystem of the Colorado River in the Grand Canyon is the only major riverine ecosystem in the Southwest where there has been an appre ciable increase rather than a decrease in riparian vegetation and associated animal populations during the 1900s. Since these Colorado River riparianlands are used by transients and wintering birds as well as breeding birds, they constitute one of the most important avian resources in the Southwest. Birds are discussed further under "Fauna."

IMPACTS OF FLOODING AND FIRE ON THE RIPARIAN ZONE

Flooding is a natural phenomenon in riparian habitats, thus riparian species are generally flood adapted. In the Grand Canyon, however, the modification of flow levels have resulted in an artificial, humanly created environment. While predam flows varied from highs discussed above to lows of as little as 1,000 cfs (28 cms) or less, postdam releases have been relatively stabilized. However, in 1983 releases through the canyon exceeded 92,000 cfs (2,600 cms), the realm of predam spring floods that originally kept the lower flood terraces scoured of woody vegetation. Under our discussion (below) on woody species we give estimates of losses to riparian vegetation at that water level (Stevens and Waring 1985). A recent USDI publication (1988) for GCES also gives summaries of the results of the floods on the riparian biota of the NHWZ. Pucherelli (1988) used aerial photography and remote sensing techniques in finding that vegetation cover in the NHWZ showed a significant increase from 1965 to 1980 and "a significant decrease in cover after the flood in 1983." "The OHWZ showed no significant change in cover from 1965 to 1980 and a significant decrease in cover from 1980 to 1985." Brown and Johnson (1985) reported damage to riparian breeding birds from nest inundation and, most seriously, habitat loss.

All known fires in the riparian zone have been humanly caused. Before development of current techniques for carrying human wastes from canyon river trips these wastes were buried on beaches and sometimes toilet paper was burned. Toilet paper fires have led to destruction of vegetation on several major camping beaches, including Nankoweap and Little Nankoweap. Tamarisk sprouts readily after fires and quickly invades burned areas. Most native species, e.g. mesquite and acacia, are more easily killed by fire and do not reestablish as rapidly as tamarisk (personal observation).

WOODY RIPARIAN SPECIES OF THE RIPARIAN ZONE

We shall address largely woody riparian species since little scientific work has been done with herbaceous species along the river. Woody species are predominant components of the riparian landscape and contribute greatly toward the support of insects and vertebrates. Additionally, woody vegetation has been studied in relation to stabilization of alluvial terraces and prevention of fluvial and aeolian erosion. It also serves as shelter for river recreationists, who spend more time on shore than on the water (Dolan et al., 1977; Johnson and Carothers, 1982).

After Clover and Jotter's (1944) original work there were no attempts to systematically treat the vegetation of the Inner Gorge until the late 1960s and early 1970s. Bennett (1969) published a list and discussion of the prevalent riparian species and between 1967 and 1971 P.S. Martin prepared a mimeographed list of the trees and shrubs of the Inner Gorge by river miles. A draft list of all known species in the river corridor was prepared at the beginning of the Colorado River Research Program by MNA researchers in conjunction with NPS (Carothers et al., 1974b). One of the better discussions of perennial riparian species and their distribution along the river is by Turner and Karpiscak (1980).

Nonnative Species

Since there have been drastic modifications to the aquatic biota of the Colorado River in Grand Canyon there has also been concern about the possible loss of riparian species due to the changed flow regimes of the river. To date we know of no riparian species that have been extirpated since 1963. As there has been a general proliferation of riparian vegetation, certain nonnative species as well as native species have increased in numbers and distribution. The most concise assessment of nonnative plants for the river corridor is given by Phillips et al. (1987):

Exotic species. . .are a minor constituent of the overall flora. . . The riparian zone along the river contains as many or more introduced species than any other area of the park, and with the predominance of salt cedar, increasing abundance of camelthorn (*Alhagi camelorum*), and herbaceous species such as yellow sweet clover (*Melilotus officinalis*) and spiny sow thistle (*Sonchus asper*) exotics certainly abound in numbers of individuals if not species along the river. . . Most exotics compete poorly with well-established, undisturbed native species, but invade rapidly and increase aggressively when habitat disturbance removes or weakens the native vegetation.

The following species of woody, nonnative plants are of particular concern. Estimates of losses from the 1983 floods are extrapolated from studies conducted by Stevens and Waring (1985) for vegetation in the NHWZ (below 60,000 cfs stage). See appendix for scientific names.

1. Tamarisk, Saltcedar: A tree or subtree, there was earlier concern about the invasion or "infestation" by tamarisk. Its spread in the canyon during the 1900s is discussed extensively by Turner and Karpiscak (1980). The historic upstream spread of the species from northern Arizona to the upper reaches of the Green and Colorado rivers was estimated at about 20 km annually by Graf (1978) who used photo comparisons and historic writings. In much of the Southwest saltcedar has out-competed native riparian

plant species, especially in disturbed habitats, e.g. those associated with dammed streams. However, saltcedar has not been known to cause the loss of plant species in the Grand Canyon.

A wide variety of strategies for growth and reproduction has lead to its success in invading riparian areas in the Southwest. These include high seed production, germination in either light or dark, and resistance to fire. In addition to saltcedar's ability to quickly colonize barren areas along beachfronts on the river, it has a high tolerance for germination and establishment in both saline and nonsaline soils (Stevens, 1989a, 1989b; ms). Although saltcedar is generally considered poor habitat for most wildlife (Anderson et al., 1977) except Mourning (*Zenaida macroura*) and White-winged doves (*Z. asiatica*) (Wigal, 1973), it is one of the canyon's most important plants for insects (Stevens, 1976, 1985) as well as the most important plant species in the canyon for riparian nesting birds (Brown, 1987, 1989; Brown and Johnson, 1989). Tamarisk is also important as shade and shelter for recreationists (Johnson and Carothers, 1982, 1987). Kunzmann et al. (1989) published a recent summary of information on this species. An estimated 44.8% of saltcedar in the NHWZ was killed by the 1983 floods.

2. Camelthorn: A spiny leguminous half-shrub that has invaded several beaches, especially in the upper portions of the canyon, making them virtually unusable for camping, at least by larger parties.

3. Russian Olive: A small tree, spreading into the canyon from seed sources originating with ornamental plantings. It has been planted in Lee's Ferry NPS campground (Johnson and Carothers, 1982) and had spread to the mouth of the Paria River by the mid 1970s (personal observation). By 1973 at least one plant was growing at the mouth of Kanab Creek (personal observation). The species has been planted to "enhance" wildlife values in riparian habitats in the Midwest (Boldt et al., 1979). Mourning Dove densities in Russian olive habitat were the highest reported for the northern Rio Grande Valley in New Mexico and Texas (Freehling, 1982). However, its spiny branches make Russian olive thickets impenetrable for recreationists. Since both tamarisk and camelthorn have proliferated profusely along the river there has been concern about Russian Olive also becoming an invasive species.

Native Species

A few of the more important woody native species of the OHWZ and NHWZ are discussed briefly here. All mortality figures for the 1983 floods are extrapolated from studies conducted by Stevens and Waring (1985) of vegetation in the riparian flood zone (below 60,000 cfs).

1. Western Honey Mesquite: A small tree or subtree occurring in alluvial deposits, mesquite was found by Martin (ms) at mi R 40.1. Now, more than 20 years later, it has not moved upstream. L. Stevens (personal com

munication) hypothesizes that large scale, scouring floods are needed to scarify the seeds that have formed "seed banks" in alluvial deposits over time. He has 6 yr. old seeds that are still viable and has had successful germination at Lee's Ferry in experimental plots.

This species is important to several riparian birds and was studied by Brown (1987, 1989). During the 1970s some bosques (woodlands) were severely damaged by camp and/or toilet paper fires (e.g., at Nankoweap and Little Nankoweap beaches). Prior to the 1983 floods some bosques along the OHWZ were obviously suffering from lack of sufficient moisture, while on some of the larger terraces mesquites were increasing in volume and threatening to interfere with campsites (personal observation). Half the canyon's NHWZ mesquites were lost from flooding, 0.9% washed out and 49.1% drowned.

2. Catclaw Acacia: A subtree co-dominant with mesquite in the OHWZ this species occurs on a wider variety of substrata; 48% killed by the 1983 floods.
3. Coyote or Sandbar Willow: A large shrub, co-dominant with saltcedar in the NHWZ Stevens (1989b) found that clonally growing coyote willow competed successfully with tamarisk. This shrubby willow is the preferred species by beaver, next to Goodding willow. The latter occurs only at scattered localities along the river (e.g., Cardenas Marsh) and, along with Fremont cottonwood, is at least partially prevented from spreading by beavers; 6.8 and 89.6% genet (plant from a single seed whether single or multiple stemmed) and ramet (single stem within a clone) NHWZ populations killed by the 1983 floods, respectively.
4. Arrowweed: This is another clonally spreading, mediumsized shrub of the NHWZ that Stevens (1989a) found successful in "dominating sand beaches which could not be colonized by seedreproducing species" e.g. tamarisk, *Baccharis* spp., and others; 33.3% and 77.6%—genet and ramet populations killed, respectively.
5. Seepwillow: A large shrub, two species, *Baccharis salicifolia*, and Emory seepwillow (*B. emoryii*) grow in the NHWZ. *B. salicifolia* is more common along the river and *B. emoryii* along sidestreams (L. Stevens personal communication); 96.8% killed by the 1983 floods in the NHWZ.
6. Desert Broom: Another, medium-sized *Baccharis*, occurring in the NHWZ of the lower canyon; 76.6% killed in the NHWZ by the 1983 floods.
7. Waterweed: A *Baccharis* morphologically and ecologically similar to Desert Broom with which it commonly occurs.
8. Apache Plume: An evergreen dominant shrub of the OHWZ. This species is relatively common downstream to about kilometer 93.3 (Turner and Karpiscak, 1980). Many of the stands of this species are in poor condition, presumably from the lack of water since the construction of Glen Canyon Dam.

HERBACEOUS RIPARIAN SPECIES

The scope of this paper allows only a cursory treatment of non-woody plants. Few investigations have been conducted with herbaceous species (Brian, 1982). The role of herbaceous species, such as their contribution toward support of riparian insects or vertebrates is unknown. Although certain species, e.g. Bermuda grass, are quite effective in stabilizing some alluvial terraces from fluvial and aeolian erosion, the role played by other species in erosion control is poorly known.

Horsetail, a non-flowering, non-woody species is a co-dominant of the NHWZ (Brian, 1982) (Figure 8-1). Herbaceous species were apparently not uncommon in the predam Ephemeral Plant Zone (Figure 8-1) and are sometimes common in the postdam Intermediate Flood Disturbance Zone (IFDZ), or second overbank flood terrace (Figure 8-2). Several other species, e.g. seepweed, are also less obvious components of either the NHWZ (first overbank flood terrace), OHWZ, or both. Common nonnative grasses include foxtail brome and, in some localities, Bermuda grass. Ephemerals and longer-lived herbaceous annuals and perennials commonly occur regularly in the NHWZ because of more mesic conditions. Xerophytic species from desertscrub communities adjacent to the riparian zone also occur in the IFDZ (Stevens, 1989a; manuscript). Herbaceous species especially occur in the OHWZ during years of higher precipitation when the adjacent desertscrub has an exceptional ephemeral blooming season, such as in the spring of 1973 (Phillips and Phillips, 1974). Postdam species consist of

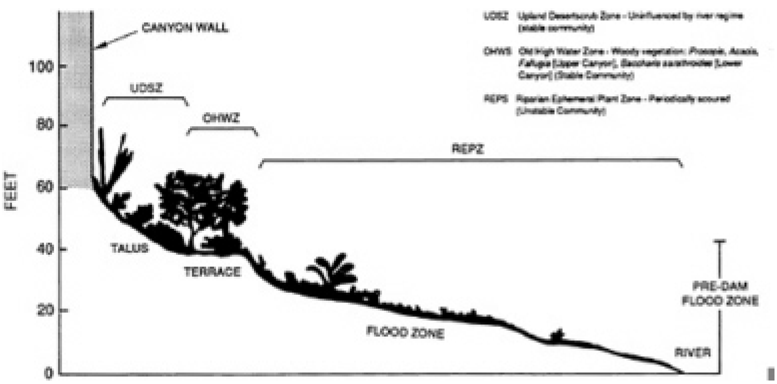

FIGURE 8-2
Profile of the vegetative zones of the Colorado River floodplain in the Grand Canyon 25 years after the impoundment of Colorado River waters by Glen Canyon Dam (after Johnson and Carothers, 1982).

both natives and nonnatives, such as those mentioned above. Herbaceous species in the IFDZ include nonnative Russian thistle, sometimes an annoyance to campers, and aforementioned native *Dicoria*. Xerophytic ephemeral from desertscrub communities also occur in the IFDZ (Stevens, personal communication).

FLORA AND CHECKLISTS

Plant checklists have been published periodically by the Grand Canyon Natural History Association. The first, in 1932, listed approximately 450 species, the second-650 species, third-900 species and the most recent, more than 1400 species (Bennett, manuscript; Phillips et al., 1987). During the Colorado River Research Program of the 1970s, 807 species of vascular plants were recorded from along the Colorado River in Grand Canyon (Carothers and Aitchison, 1976) and at least two species of flowering plants new to science were discovered—*Euphorbia aaron-rossii* (Holmgren and Holmgren, 1988) from Marble Canyon and *Flaveria mcdouqallii* from Cove Canyon, a tributary of the Colorado (Theroux et al., 1977).

FAUNA AND CHECKLISTS

Numerous species of plants and animals were added to lists of the Grand Canyon biota during scientific investigations along the Colorado River in the 1970s. All of these newly discovered species are not from the river corridor but the work being done along the river served as a stimulus to gather additional information for updating these checklists. As discussed earlier for the flora, it is difficult to determine which species were added to the list because of increased studies of this remote region and which species have recently entered the park. Some species have been added to park checklists by extending the definition of "Grand Canyon" (Tomko, 1975) and by boundary extensions, thus increasing the size of the park.

Amphibians and Reptiles (Herps)

The most recent checklist for herps is by Miller et al. (1982). Previously, Tomko (1975) added nine species to Gehlbach's (1966) checklist (referenced by Tomko but not Miller et al.). Amphibians in general are associated with moist habitats. Of the one species of salamander, and five toads and frogs in three families, listed by Miller et al. (1982) for the park four of the latter occur along the Colorado River. Woodhouse's toad (*Bufo woodhouseii*) is restricted to the Colorado River corridor and the leopard frog (*Rana cf. pipiens*) is restricted to Cardenas Marsh, RM 71 L (Tomko, 1975), a postdam marsh, and Upper Lake Mead (Stevens, 1989c).

Reptiles in general are adapted to xeric environments, and while many of them are *nonriparian or facultative* riparian species others occur in riparian habitats either as *obligate* or preferential riparian species (terms after Johnson et al., 1984). Rattlesnakes, for example, are often considered inhabitants of xeric, often rocky habitats. However, the best known of the canyon's reptiles, the Grand Canyon (or pink) rattlesnake (*Crotalus viridis abyssus*) frequently occurs in riparian habitats (personal observation; Miller, 1982). Warren and Schwalbe (1985) listed seven species of lizards for the riparian zone along the river. Stabilization of river flows has probably resulted in an increase in herp populations through greater vegetational biomass, providing in turn more cover and an increase in insect availability, as discussed below for birds.

Birds

The importance of riparian habitat along this corridor to the avifauna of the region has been documented by a series of recent studies by Brown, Carothers, Johnson, and associates. During the Colorado River studies of the 1970s Carothers and Johnson (1975) published new distributional records for 20 birds in the Grand canyon region, seven of them additions to previously compiled faunal lists. By 1978 the number of species known for the Grand Canyon region had grown to 284 (Brown et al., 1978), adding more than 100 additional species to the 180 in the first Grand Canyon checklist (Grater, 1937). By 1987 this had increased to 303 avian species (Brown et al., 1987) of which 250 (83%) have been recorded from the Colorado River corridor (Brown et al., 1985).

The avifauna is the best studied biological component of the Colorado River. The high visibility of birds provides relative ease of scientific study, and the interest of amateurs (including river runners) results in a larger number of records than for other animals. Thus, several recent findings about the avian ecology of the river may be used to partially illustrate the role of vegetation in the riparian ecosystem. Since 1964 and publication of *The Birds of Arizona* (Phillips et al., 1964), nesting populations of at least six riparian species have become established in the Grand Canyon (Johnson and Carothers, 1987) and populations of several other nesting species have greatly increased. The gradual upstream movement of Bell's Vireo with increasing riparian vegetation was documented by Brown et al. (1983). Populations of nesting birds in tamarisk approaches the highest numbers for temperate North America (Brown and Johnson, 1989).

The most extensive general studies with riparian birds in the Grand Canyon have been by Brown (1987, 1989). His findings, broadly generalized, are that in the Grand Canyon obligate riparian nesting birds select tamarisk over native plant species for nesting habitat. Additionally, individual nests are preferentially placed in a tamarisk bushes instead of native plants, e.g., coyote willow, arrowweed, or seepwillow, even when other species are equally available.

Proliferation of vegetation in the postdam riparian ecosystem is largely responsible for the increase in numbers and species of birds. The reasons for selection of tamarisk over native species are not so clear. However, studies by Stevens (1976, 1985) have shown a disproportionately large number of individuals and species of insects supported by tamarisk. Since nearly all breeding avian species along the Colorado River are insectivores these high insect populations presumably provide an abundant avian food source. However, this still does not explain the preferential selection of tamarisk over other species for nesting.

Mammals

Ruffner and Carothers (1975) published new distribution records for twelve mammalian species, including two new species for the park since the publication of *Mammals of Grand Canyon* (Hoffmeister, 1971). Many of these additions were from the river riparian zone. Some of these species, as with herps and birds, have undoubtedly increased in numbers and/or distribution in the region because of proliferation of riparian vegetation with resultant increased cover and food availability. Of the 78 species of mammals listed by Hoffmeister (1971), Ruffner and Carothers (1975), Ruffner et al. (1978), and Suttkus et al. (1978), Jones et al. (1982) and Stevens (1989c); 40 (51%) occur in the Inner Gorge. Most occur in the riparian zone, either as obligate riparian mammals, e.g. beavers, or some lesser category of usage, e.g. desert bighorn sheep that only use it on occasions. An outstanding treatment of mammals of the area is found in Hoffmeister (1986).

The importance of vegetation to animals, as food and shelter, has been emphasized earlier. In some situations, e.g., for herbivorous mammals, animals may, in turn, have a profound influence on vegetation. Burros caused notable damage to riparian vegetation by foraging and trampling (Carothers et al., 1976) and reduced populations of some plant species by selective foraging prior to the removal of these feral mammals from the canyon. One of the major factors in the lack of establishment of Goodding willows and Fremont cottonwoods along the river is their utility to beavers (personal observation). Beavers also eat the smaller, coyote willow and even tamarisk. At a small beach at Tapeats Creek beavers totally stripped coyote willows and tamarisk, leaving nothing but seepwillows by the fall of 1989 (L. Stevens, personal communication). Such foraging could result in significant biogenic succession, producing a "beaver disclimax" on some beaches, if beaver populations reach adequate levels. One of the more poorly understood vegetational parameters for most woody riparian species is seedling establishment. Ecesis (germination and establishment) of riparian species in the canyon is being studied by Stevens (1989a). Findings from these studies and subsequent monitoring programs are critical to the management of the riverine ecosystem in Grand Canyon.

THREATENED AND ENDANGERED (T & E), RARE, AND ENDEMIC SPECIES

Riparian

The Colorado River corridor, with its linear ribbon of open water and riparian habitat, comprises the largest amount of this type of habitat in the region. Moisture furnished by the river serves as an ameliorating influence, providing a series of more mesic environments in this generally and landscape. Still, the Grand Canyon region is notably short on endemic, rare, and T & E species for such a large, diverse area. Two previously undescribed species of flowering plants, *Flaveria mcdougallii* and *Euphorbia aaron-rossii* were mentioned earlier in the paper (Carothers and Aitchison, 1976; Phillips et al., 1987). This small number of special status species is probably due in large part to the Colorado River's running the entire length of the region, bisecting and connecting the various sections of the Colorado Plateau and providing a relatively uniform environment that serves as a dispersal route for many species of plants and animals.

Of as great interest as the presence, or lack thereof, of special emphasis species are species that are lacking. The house mouse (*Mus musculus*), for example, is missing as are species of old world rats (*Rattus*) that are found in many of the more "civilized" parts of the United States. Feral burros, on the other hand, built up to such high populations along the Colorado River during the 1970s that they unfavorably impacted both the natural riparian environment and recreational activities (Carothers et al., 1976).

Endangered Species

Two endangered birds of the riparian zone are the Bald Eagle (*Haliaeetus leucocephalus*) and Peregrine Falcon (*Falco peregrinus*). Bald eagles have become regular winter visitors since the mid-1980s (Brown et al., 1989) in the vicinity of Nankoweap Creek and the river where they feed on fish. Numbers have increased to more than 50 individuals (B. T. Brown; L. Stevens, personal communication). Recent studies by S.W. Carothers and B.T. Brown (personal communication) have demonstrated that the Grand Canyon supports the highest concentration of breeding Peregrines in the lower 48 states. A total of 71 different Peregrine breeding areas were documented during partial investigations of the region in 1988 and 1989 (Brown, 1990). A large percentage of the Peregrine's diet consists of birds caught over the riparian and aquatic zone of the inner canyon.

AQUATIC

Aquatic ecosystems are extensively discussed elsewhere in this volume. However, this discussion of the riparian zone would be incomplete without some mention of the interactions with the adjacent river with which it so intimately communicates. For example, riparian birds are largely insectivorous, with different species foraging to varying degrees on insects that have aquatic stages in their life cycles. Although insects have been studied in the Grand Canyon (Stevens, 1976, 1985), more definitive information is needed to ascertain the role of vegetation in insect life histories, and the role played by insects as food for riparian as well as aquatic organisms. In addition to sedimentological studies discussed elsewhere in this volume, the contribution of sediment, nutrients, and detritis from the riparian zone to the aquatic food chain needs to be further investigated.

The Lee's Ferry area is one of the nation's finest rainbow trout fishery. By the early 1900s, the transplanting of nonnative species into the Colorado River had become common largely because of the advent of trains, the tank car, and other efficient means of transporting fishes. "Game fish" were common enough at Lee's Ferry by the 1950s to attract fishermen (S. Carothers, personal communication). As mentioned earlier, approximately 1/2 of the 100,000 annual visitors to the Lee's Ferry area are fisherman that use the riparian zone extensively for camping, shelter, and bank fishing.

The role of these introduced fishes in reducing and/or extirpating native fishes within the Grand Canyon is not clearly known. Johnson and Carothers (1987) have proposed that predation by nonnatives has played a larger role in extirpation of these native species than some have noted. Many of these species are voracious predators on young of larger native species or adults of smaller natives. Additionally, carp had arrived in Arizona prior to 1885 and although they generally do not feed on small fishes they do eat fish eggs (Minckley, 1973). Thus, during most of this century native fishes of the Colorado system have had to compete with these introduced species (Minckley and Deacon, 1968).

Carothers further proposes that, based on his studies of the fishes of the Colorado River in Grand Canyon (Carothers and Minckley, 1981), several native species were nearing extinction before the construction of Glen Canyon Dam (see also Minckley, this volume).

SUMMARY AND CONCLUSIONS

The Colorado River in Grand Canyon, as other riverine systems throughout the arid Southwest is characterized by a close interrelationship between aquatic and riparian components of the ecosystem. Riparian ecosystems provide nearly classroom examples of ecotones, occurring at the interface of aquatic and terrestrial ecosystems. As such, they demonstrate the edge effect by showing an increase in species richness and population densities. We have here discussed both riparian organisms and processes as well as aquatic-riparian ecotonal interactions along the Colorado River in Grand Canyon.

The importance of this riparian habitat to the nesting avifauna of the lowland Southwest, other wildlife, and humans has been widely documented. The riparian zone in Grand Canyon is used extensively by whitewater recreationists, hikers, and a large number of native animals. Since these riparianlands are used by transients and wintering birds as well as breeding birds, the Colorado River riparian ecosystem constitutes one of the most important avian resources in the North American Southwest.

Riparian desertification is a major problem throughout the and South-west. However, the riverine environment in Grand Canyon has become increasingly mesic, contrasting with increasingly xeric conditions of most riverine ecosystems of the Southwest. Thus, riparian vegetation in the canyon is uniquely valuable since the Colorado River in Grand Canyon is the only major riverine ecosystem in the Southwest where there has been an appreciable increase rather than a decrease in riparian vegetation and associated animal populations during the 1900s.

Continuing scientific investigations in the Grand Canyon need to examine the interrelationships between water releases from Glen Canyon Dam and the riparian and aquatic ecosystems of the downstream Colorado River. Biological components of these ecosystems need to be closely examined in relation to the physicochemical environment. Discussion of some of the research needs in examination of the intricate interrelationships between the riparian and aquatic ecosystems of the Colorado River in Grand Canyon are mentioned in the aquatic section, above. Of equal importance is the determination of socioeconomic factors and the examination of carrying capacity and visitor satisfaction as discussed by numerous investigators (Heberlein and Shelby, 1977). Although the native riverine ecosystems are no longer extant, strategies for the proper monitoring and management of the existing naturalized riparian ecosystem and exotic aquatic ecosystem must be addressed if the viability and utility of the Colorado River in the Grand Canyon is to be maintained.

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APPENDIX A

Apache Plume-*Fallugia paradoxa*
Arrowweed-*Tessaria (Pluchea) sericea*
Bermuda Grass-*Cynodon dactylon*
Brome, Foxtail or Red-*Bromus rubens*
Bulrush-*Scirpus americanus* and *S. validus*
Cactus, Barrel-*Echinocactus polycephalus* and *Ferocaclus acanthodes*
Camelthorn-*Alhagi camelorum*
Catclaw, Catclaw Acacia-*Acacia greggii*
Cattail-*Typha domingensis* and *T. latifolia*
Clover, Sweet-*Melilotus* spp.
Cottonwood, Fremont-*Populus fremontii*
Creosotebush-*Larrea divaricata (tridentata*)
Desertbroom-*Baccharis sarothroides*
Dicoria-*Dicoria brandegei*
Horsetail-*Equisetum* spp.
Mesquite, Western Honey-*Prosopis glandulosa*
Ocotillo-*Fouquieria splendens*
Russian-olive-*Elaeagnus angustifolia*
Seepweed-*Suaeda torreyana*
Seepwillow-*Baccharis salicifolia (glutinosa*)
Seepwillow, Emoryils-*B. emoryii*
Tamarisk, Saltcedar-*Tamarix ramosissima*
Thistle, Russian-*Salsola iberica*
Thistle, Sow-*Sonchus asper* and *S. oleraceus*
Waterweed-*Baccharis sergiloides*
Willow, Coyote-*Salix exigua*
Willow, Goodding-*S. gooddingii*

9

Reservoir Operations

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INTRODUCTION

What is a reasonable structure for a set of models for the Glen Canyon Dam (GCD) operation problem. The system appears to require at least two types of model: (1) a reservoir hydrology model with monthly time steps and (2) a model of releases with hourly time steps to capture the hourly variation in value of hydropower and to characterize downstream flows—input to a routing model or to other models for environmental parameters that are affected by diurnal flow and ramping rates. Modeling explicitly flows or energy every hour for a period of several years is possible but not very useful, because the results are impossible to interpret except in the form of a statistical summary. Thus, the conventional approach to providing input to the parameters of such a very short term energy model is the excedance curve (basically a cumulative distribution function [CDF]) representing the fraction of time for which a parameter is greater or less than a selected level. There are pitfalls that often distort analysis of systems using the excedance approach. One is related to errors introduced by averaging (to be demonstrated later). A second source of error is the loss of ability to model head on turbines explicitly.

An oversimplified but useful graphic representation of the approaches used to date to model the GCD operation is given in Figure 9-1.

Since much of the flow into Lake Powell is regulated by several upstream reservoirs, the initial hydrograph shown in Figure 9-1 represents either historic data or output from a large multireservoir operation model, which is not shown.

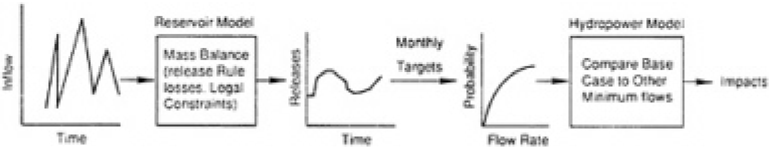

Figure 9-1
Relationship of hydrology and energy models.

The reservoir simulation model converts reservoir inflow data into a trace of time-related releases (for which storage, and therefore water level, in the reservoir is explicitly known). The short-term model converts this trace into an excedance function, thereby losing the ability to associate correct heads with flows. It is therefore necessary to select a single (average) value of head for the entire analysis (usually a year) to translate flow rates into energy and/or power. This is not a serious problem for normal operation of GCD because the variation of water level over a year is usually only about 5% of the total; in a drought year, however, it can approach 10%.

ANNUAL OPERATION WITH MONTHLY TIME STEPS

The USBR Reservoir Model

The Colorado River Storage Project (CRSP) is a multireservoir system. GCD is the downstream end of the system; upstream reservoirs include Flaming Gorge, Fontanelle, Navajo, Crystal, Blue Mesa, and Morrow Point. GCD, however, represents 79% of the storage capacity and 78% of the generating capacity of CRSP. One hundred percent of the upper Colorado flows (except for the small Pariah) pass GCD.

About half of the flow into Lake Powell is unregulated, and half is a function of the operating rules at the other upper basin reservoirs. Lake Mead is the only downstream reservoir that should be considered in a model of the operation of GCD, and the only reason for including this reservoir is a politically imposed constraint that at the beginning of each water year, the storage intake of Lake Powell cannot exceed that in Lake Mead. From the perspective of comprehensive river basin planning, this constraint is not a wise policy. One of the basic tenets of good multireservoir system operation is that one always keeps as much of the water as possible as high in the system as possible for as long as possible (within reasonable flood control criteria), because water can always quickly be moved to a lower reservoir as needed but can never be moved back if a mistake is made. The reason that this constraint was imposed in this case has to do with upper and lower basin politics and who has control of subsystems rather than total system operating efficiency.

A simulation model of the entire river called CRSS has been developed by the U.S. Bureau of Reclamation (USBR) (Schuster 1987, 1988a,b). The model structure appears to be totally adequate for the monthly time step hydrologic analysis required for the GCES program. There should, however, be a detailed review of the demand input data base (SMDDID) in regard to updating the assumptions on the level of future upper basin diversions from the river. Past assumptions on the timing and extent of development of upper basin projects are undoubtedly obsolete, given the major cutback in federal funding of future projects.

The principal losses of water from Lake Powell are evaporation and bank storage. Average annual evaporation depths from Lake Powell have been estimated by the RANN research program at 70 inches (Potter and Drake, 1989) and by Hughes et al. (1974) at 68 inches. Evaporation, of course, varies significantly with climatic variations, but the expected value must be used in a planning model since the climate cannot be forecast. The RANN estimate is probably best, since it was determined by actual pan measurements located on the lake. Evaporation from the upper basin reservoirs during typical years (when Lake Powell was almost full and had an average surface area of 156,000 acres) was estimated by the CRSS model as 0.73 million acre-feet (maf) (0.61 maf in Lake Powell and 0.12 total maf in other reservoirs). The 0.61 maf figure implies a depth of only 47 inches. The difference between 70 and 47 inches is too much to be explained as a correction for rainfall (about 6 inches per year), which now falls directly on the lake but used to be mostly lost to evapotranspiration within the area inundated. It therefore appears that the CRSS model underestimates evaporation by about 24%.

As more data become available on reconciliation of theoretical versus actual mass balance of parameters in the reservoir and releases from GCD versus flows at Lee's Ferry, the way in which bank storage in Lake Powell is modeled should be improved. The current practice of estimating it as 8% of the change in storage regardless of water level was previously necessary because no empirical data were available in the early years of operation to justify a better approach. This parameter, however, represents about 8 maf of water (Potter and Drake, 1989) and should be given more attention now that some 25 years of operation data are available. This factor is not important during cycles of close to normal or wet years when the reservoir fills each July, but during an extended drought, bank storage would become a very important asset (and also an important liability in slowing refilling of the reservoir after a drought).

Various hydrologic data bases are used for long-term planning studies by CRSS. The data, which began in 1906 and continues to date, include: (1) virgin flows, i.e., data modified to remove the estimated effect of diversions and reservoir regulation, and (2) depleted flows, i.e., data modified to simulate flows as if no reservoirs exist (and therefore evaporation is not part of the depletion). Depletions at current levels are imposed over the entire period of record in this data base. The effects of reservoir regulation, evaporation, and bank storage are functions of the reservoir operating rule and therefore cannot be included in the data bases.

Modes of Operation for CRSS

Uses of the CRSS model depend on the objective of the user. Long-term planning studies use the entire 80-year data base for determining statistical properties of the hydrology, frequency of floods and droughts, etc., and may also develop synthetic hydrologic sequences of flows. The real-time operation problem, however, uses a different version of the model to predict state of the system 24 months into the future. Although this model exists on a mainframe computer at the USBR Denver Research Center, a microcomputer version of the 24-month planning model has been developed by the Upper Colorado River Commission (1987) in Salt Lake City, using only a spreadsheet.

Other Reservoir Models

Another simulation model of the Colorado River that has received some attention in the literature was developed jointly by the Rocky Mountain Forest and Range Experiment Station and WBLA, Inc. (Brown et al., 1988, 1989). This model uses software developed originally for the Texas Water Resource Planning Agency. It has since been used extensively by researchers at Colorado State University. The essential difference between this model and the CRSS model is that the WBLA model has a within-month optimization algorithm which allocates water during a particular month in a way that maximizes an economic objective (dollars per acre-foot in various uses) subject to the river compacts and other statutory priorities on releases. This model should not be confused with an optimization model that optimizes releases over a planning horizon such as a year. The optimization is only on allocation among users within any month. The determination of releases, for example in July versus May, is done in a simulation framework (same as the CRSS model), which is to say that the monthly operating rule is assumed, not optimized as it would be by using a linear decision rule or a dynamic programming model.

Who Operates the Dam?

The simple and realistic answer to this question is: USBR determines monthly (and therefore annual) releases, and the Western Area Power Administrtion (WAPA) operates the dam in real time, subject to meeting the USBR monthly targets. The official answer to this question contains a long list of caveats about coordination with other interested parties. Since the embarrassing flood damage of 1983, this coordination has taken the form of a Colorado River Management Work Group chaired by USBR and consisting of representatives from each state, the Upper Colorado River Commission, and WAPA. Barry Saunders (the Utah representative) reports: "For over five years, the sevenstate Governor's representatives (and Management Work Group) have been functioning with increasing efficiency in balancing water supply and flood control requirements. To date the process has not been utilized effectively for addressing environmental issues" (Saunders, 1989).

USBR Operating Plan

Glen Canyon Dam (along with all other dams in the upper basin) is operated by using information derived from a 24-month operating period version of the CRSS model. Each run of the model includes the last 12 months plus a monthly projection for the next 24 months. Releases are conditioned in the near term (the snowmelt season) on both water content of the snow and antecedent precipitation (a surrogate for soil moisture conditions). Projections for the second year are presumably based on expected values. The current USBR approach to determining future releases is not an explicit one, such as would be obtained from a linear decision rule, but rather is a heuristic approach developed by considering both an optimistic and a pessimistic range of runoff from current snowpack and observing the resulting range of storage results. The procedure is then repeated monthly, and projected flows are updated by using actual current storage and revising future inflow estimates conditioned upon current snowpack conditions. The magnitude of typical correction to original projections needed during a drought period is shown in Figure 9-2, which displays the initial projection and the final measured releases from GCD for the USBR 2-year projection of monthly releases during calendar years 1988 and 1989. The variations by no means indicate deficiencies in the operating rule but rather display the degree of hydrologic uncertainty facing the planner.

An oversimplified description of the criteria used to determine the annual release targets is as follows.

Annual Release at Lee's Ferry—Only the 8.23-maf average minimum required by the compact plus the Mexican treaty will be released unless there is a significant probability of spills during the next runoff season. In this context, spills are defined as flows that bypass the turbines.

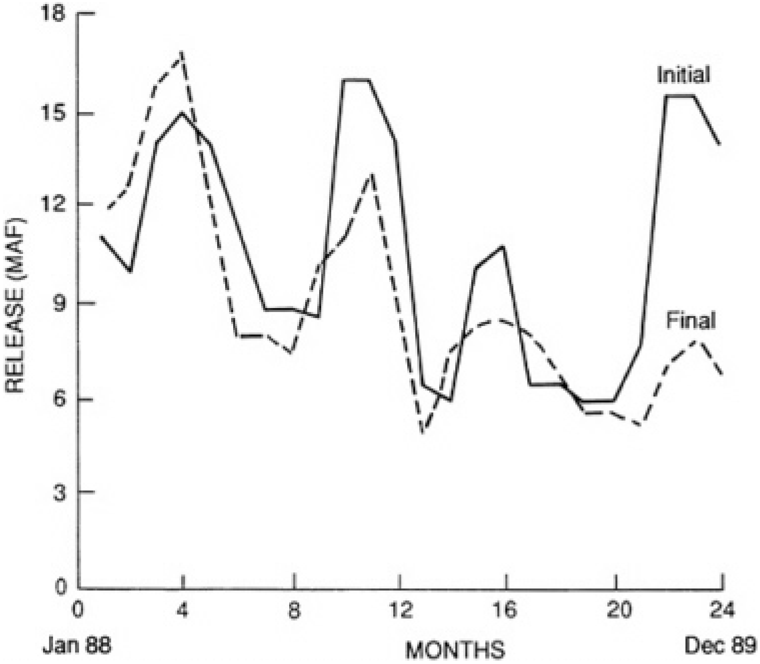

FIGURE 9-2 Variation from the initial to final operating plan.
SOURCE: USBR, 1989.

Monthly Target Releases—Within a year, the monthly targets are allocated to create a flood storage space of 2.4 maf on January 1 and to be within 0.5 maf of full by July 1. Prior to 1983, the July target was a totally full reservoir (25 maf of active storage above the river outlets), but the 0.5 compromise was recently agreed upon by the operations management group. The USBR statistical analysis of the hydrology concludes that this change will decrease the probability of a spill from .25 to .05.

Where possible, the monthly targets are also shaped to improve the ability of WAPA to better follow the seasonal peaks and valleys in energy demand. For example, targets in winter and in summer are somewhat greater than those in spring and fall. These fluctuations, however, are much less extreme than the daily fluctuations to be discussed later (they typically vary from 0.5 to 1.0 maf, and some of this variation is due to flood/conservation balancing rather than energy considerations.

There is no reason to shape monthly releases from GCD to follow the seasonal irrigation pattern of releases in the lower basin because Lake Mead can regulate such variations. The only exception to this is the requirement to not exceed the Lake Mead storage at the end of the water year (September 30).

SHORT-TERM OPERATION OF THE DAM

For the monthly hydrology model discussed above, it was necessary to draw the system boundary around the entire upper basin. Given the output of that model, however, a smaller boundary is adequate for the short term model. Hourly releases from upstream reservoirs are totally redundant for modeling GCD releases necessary to capture the impact of revised minimum instantaneous flow rates. Also, monthly release targets (the USBR operation decisions) that are both feasible and desirable are essentially independent of minimum flow rates (the WAPA operating decisions). If flows at night are increased, daytime flows must be decreased to still meet the monthly target. There are, of course, minimum release criteria which would be infeasible. For example, a monthly target of 0.5 maf is a constant flow of 8,300 cubic feet per second (CFS). Clearly, a higher minimum release would be infeasible. Increases in minimum flows have no effect on total hydropower generated because the same volume of water at the same head (except for minor changes in backwater levels) passes the turbines by the end of a month. Either this volume will equal the monthly target or any deviation from the target can be corrected early in the subsequent month. Only the value, not the quantity, of energy is changed by the minimum flow criteria.

Short-term models of reservoir releases and their translation into energy are traditionally done in terms of excedance functions or CDFs (the probability of flow exceeding any given level) as opposed to the monthly hydrologic model, which captures sequentially for each time step the mass balance of inflow and outflow from a system. Therefore, it is therefore appropriate to discuss the implications of this modeling approach. In interpreting such information, it is important to know both the time step of input data used to generate the excedance function and also what averaging was done before the CDF was developed. Consider the peak period and off-peak period CDFs in Figure 9-3. These excedance curves were developed from hourly data for the 13 years since the lake approached a normal operating mode (1978–1989). They indicate that release rates are below 5,000 and 8,000 cfs 30 and 47% of the time, respectively, during hours when energy is at low value (nights) and 5 and 12% during peak valued hours. The functions also show that flows were above the 31,000–33,000-cfs capacity of the turbines 5% of the time (during the flood of 1983 and 1984).

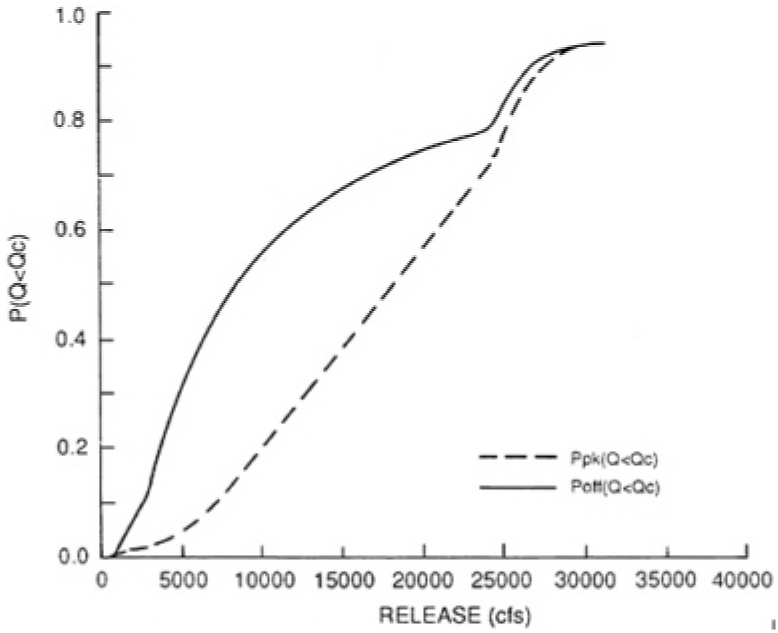

FIGURE 9-3
Glen Canyon Dam release probabilities during peak and off-peak hours (1978–1989).

WAPA MODELS OF INCREASED MINIMUM FLOWS

GCES I Model

In response to the NRC review of a draft of the GCES I report, WAPA was requested to develop (rather quickly) an analysis of the probable economic impacts of increasing minimum releases from GCD from 1,000 or 3,000 to 5,000 and 8,000 cfs all year. They produced a report (WAPA, 1988) which estimated $5.0 million and $14.7 million of increased annual cost to energy users during the next decade and much larger increases after 1999.

WAPA's approach to this calculation was to define a base case representing historic dam releases during the entire period of record (1965–1987) as a reference from which to estimate increases in off-peak and decreases in on-peak water releases and then to translate these water release changes into changes in generating capacity (megawatts) and energy (megawatthours). The data from which the base case was developed were monthly releases for the 23 years of operation of GCD, from which time-of-week excedance functions were developed. From these excedance functions, the flows related to probability levels upon which firm capacity (capacity available 90% of the time) and energy marketing (average historic megawatt hours) are based were determined. The complex analyses of changes in firm and nonfirm sales, fuel replacement sales, and wheeling of energy from other sources were all then calculated as functions of incremental changes from this base case.

The time-of-week excedance function used for the base case was derived not from hourly data (even though they were available) but by assuming constant flows equal to minimums allowed (1,000 cfs in winter and 3,000 cfs in summer) 100% of the time during off-peak hours. The peak-hour releases were then calculated by allocating the remaining volume of water in the monthly data base to these hours. Peak hours on weekends were assumed to be at about 48% of the weekday peaks.

The difference between the WAPA results and the actual average monthly peak and off-peak releases are displayed for 1982 (a slightly above average inflow year) in Figure 9-4. The assumption that actual off-peak flows equal minimum flows is extremely bad. It introduced an error of as much as 700% in winter (always too low) and was never closer than 33% to the measured data during summer. The annual average during off-peak hours is closer to 6,000 than to 1,000 or 3,000 cfs. This initial assumption caused a consistent overestimation of peak flows for the base case (also shown in Figure 9-4). The analysis then proceeded by changing the bottom line in the figure to a constant 5,000 or 8,000 and lowering the peak period flows as required to maintain the same monthly mass balance. It is very difficult to place any credence in the accuracy of the 1988 WAPA economic impacts, given the large errors in the basic assumption which drives all subsequent calculations in the report.

Although only a single year is shown in Figure 9-4, the conclusion would be the same for any year in the 23 year data base used by WAPA: off-peak flows are at the minimum allowed during only a small fraction of the time, and therefore the analysis must be based on expected values determined from hourly data, not from an assumption of constant flow at minimum level.

A logical question arises from the results shown in Figure 9-4: Since it is in WAPA's interest to operate GCD at the minimum possible release level during off-peak hours, why was this such a bad assumption (why don't they operate that way)? The answer is evident from observing the truly random energy load that the dam operators are attempting to follow. An example of hourly actual generation (July 1982) is shown in Figure 9-5. Although the scale is in megawatts, it can easily and with reasonable accuracy be interpreted as flow in cubic feet per second (given the knowledge of an essentially full reservoir for calculating head) by using a conversion of 1 mw = 25 cfs. The minimum July release of 3,000 cfs (120 MW) is seen to occur on several days, but only for 1 or 2 hours at a time. Another way of reaching this obvious conclusion is that if a random variable has a high variance and has a lower bound of 3,000 cfs, its expected value is always going to be much higher than 3,000.

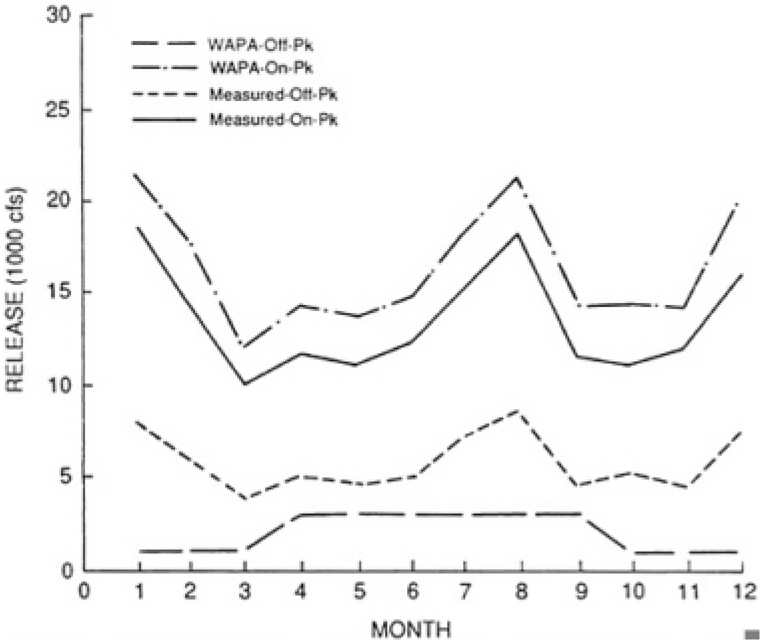

FIGURE 9-4
Comparison of WAPA 1988 model and actual measured data (on-peak and off-peak, 1982).
SOURCE: WAPA, 1988.

One should note that even though average releases in off-peak periods were greater than 5,000 cfs during the example year discussed above, it should not be concluded that raising the allowable minimum to 5,000 will have no effect. From reasons discussed above, an operator following a new random load and a higher minimum release will produce an average release higher than before, and therefore the change will have an economic effect. How much higher than the previous off-peak original average is the difficult question upon which the GCES 11 operations study should be focused.

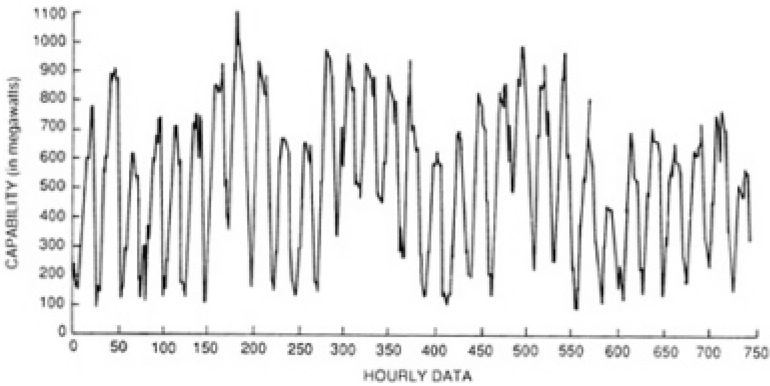

FIGURE 9-5
Actual generation for July 1982.
SOURCE: WAPA, 1982.

The answer to this question was obvious for the assumption used by WAPA—if the base case flow is always at the minimum, then the alternative minimums also should equal the flow during off-peak hours. With the much more accurate assumption, however (the expected value of average flows during off-peak periods), the increment of increase is not obvious. The effect in the short run may be minor because there will be no change in the firm power contracts (only in the other types of purchases and sales) and therefore no change in the load. In the long run (new contracts), increased minimum flows will likely motivate an increase in the firm contract requirement of off-peak minimum capacity and energy equal to 35% of peak period. Although the current 35% requirement is much greater than the minimum related flows, it is not necessarily greater than the average resulting from higher minimums, and periods when load is less than minimum generation could result if this contract requirement is not increased.

OTHER RELATED WAPA REPORTS

Report on Impact of Alternative Interim Flows

WAPA has also produced a report related to the impact of possible increased minimum flows during the next 5 years (WAPA, 1989). This report presented results in a much different framework than the 1984 report, fo cusing on decrease in flexibility of marketing due to these possible alternative flows. Details of the method used related to the model logic for the base case were not included. It will therefore not be reviewed here; however, there is no indication that anything other than monthly data were used for the analysis.

Report on Cost of Research Flows

WAPA has produced a report on the economic impact of experimental flows planned by the GCES II program during 1990 and 1991 (WAPA, 1990). The estimated cost was $10.9 million. The report is documented very well (thank you), which allows an analysis of the model logic similar to that of the 1988 report. The all important base case was developed as follows: the CRSP load during 1990–1991 was assumed to be the actual load (78% of which was at GCD) for 1989, and the monthly averages for peak and off-peak periods were calculated by using hourly data. The load, however, is not the same as the generation pattern at GCD because of fossil fuel purchases and other transactions. The base case generation pattern at GCD was therefore estimated in a manner similar to that used for the 1988 report except that the assumed minimum releases were increased to 1,000 cfs above the minimum flows of 1,000 and 3,000 cfs. This results in off-peak volumes of 2,825 acre-feet (8 hours/day) in summer and 1,325 acre-feet during off-peak hours in winter. This increase recognizes that a random variable cannot have a mean equal to its minimum. Again, however, this step in the right direction appears to be too small. Figure 9-6 compares the actual measured values for 1989 peak and off-peak generation from GCD to those used for the WAPA base case. The summer off-peak model (months 4 through 9) is reasonably accurate except for one month, but again, the winter model is in error by more than 100%. The underestimation of off-peak releases results in an overestimation of base-case peak period releases, as shown by the difference between the two upper lines. This resulted in a corresponding overestimation of the impact of the experimental flows.

GCES ECONOMIC TEAM PROGRESS TO DATE

The GCES II economic study team has completed an initial report (Bureau of Reclamation, 1990) on one important aspect of the way in which the impact of increased minimum flows should be analyzed—that is, what type of model is best for predicting the nature of the response to increased minimum flows by large utilities that are firm power customers of CRSP. The implication of this question is that if the ability of GCD to provide peaking energy is reduced, an increment of capital investment (and related increased operating cost) in some type of alternate source will, at some future time, be required. The approach used in this report (Bureau of Reclamation, 1990) to solve this investment timing problem was to develop a hypothetical system including three firm power customers that each have other sources of energy. This system was then modeled by three different approaches: (1) ELFIN-an energy system simulation model developed by the Environmental Defense fund; (2) EGEAS-an investment timing optimization model used by the Electrical Power Research Institute; and (3) ATPM (alternate thermal power method), which is a much simpler approach sometimes used by WAPA to the estimate cost of an alternate source.

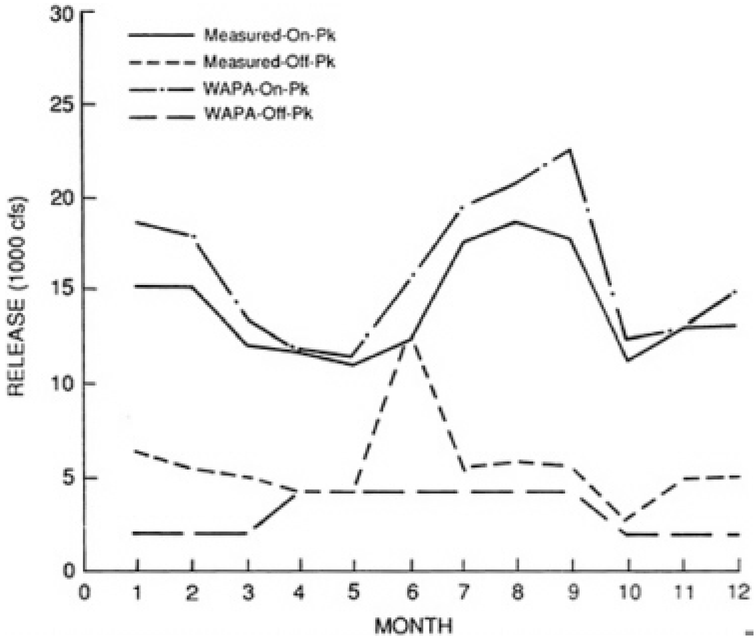

FIGURE 9-6
Comparison of WAPA model and actual measured data (on-peak and off-peak, 1989).
SOURCE: WAPA, 1989.

The report's conclusion is that both ELFIN and EGEAS should be used in the GCES study and their results should be compared. It should be noted that the focus of the report is on the investment timing and estimation of which type of alternative energy source is likely to result from changes at GCD. The economics/operation study team has not yet addressed the more basic problem (how much impact in peaking capability will result) that was addressed in the WAPA reports discussed above. It is likely that any reasonable approach to the investment timing problem and the selection of which type of generating source is likely to be added will be adequate, because this information is much less important to the total question of evaluating impacts than are the basic assumptions that drive the calculation of the megawatts and megawatt-hours of reduction in peaking capability at GCD. Consider that while GCD is 78% of the CRSP capacity, CRSP is only 13% of the WAPA system capacity, and WAPA represents about 1.3% of the entire western U.S. generating capacity. A loss, for example, of 20% in GCD peaking capacity would be a 0.25% loss to the system from which ELFIN and EGEAS are attempting to model impacts. The probability of accurately predicting the future impact of such a marginal change in this very large system seems very low.

Ramping Rates

One parameter that is related to environmental objectives but was not modeled in previous WAPA reports is the rate of change of releases from GCD —the ramping rates. The research releases requested by GCES, however, specifically require both high and low ramping rates. It was necessary for WAPA to define the terms *high* and *low* before the cost of these flows could be modeled in the 1990 report on cost of research flows. The terms were therefore interpreted as high = 7,200 cfs/hour and low = 3,600 cfs/hour. The ramping rate, either up or down, can be viewed as the derivative of the release hydrograph. In the WAPA report, the shape of the daily-release hydrograph is determined by assuming that ramping up begins at 8 a.m. (the first hour of the peak period) and ramping down ends at midnight (the beginning of the off-peak period). This means that the entire off-peak period is modeled at the lowest rate and all ramping occurs during the peak hours.

The typical historic pattern is difficult to summarize. The average hourly release rates for each month for 1982 are shown in Figure 9-7. Note that the winter months have two distinct peaks (one at 9 a.m. and another at 7 p.m.) The ramping up begins at 5 or 6 a.m., and it would therefore appear to be more accurate to model the beginning and end of ramping during off-peak hours, perhaps splitting the ramping period between the two periods about equally. The summer months have a single daily peak (except for April, which has the winter-month shape), with ramping beginning at 6 a.m. and peaking at 2 p.m.

Care should be taken in making conclusions about ramping rates from Figure 9-7; however, the points each represent averages of about 30 values each hour, which eliminates much of the randomness. To get a better

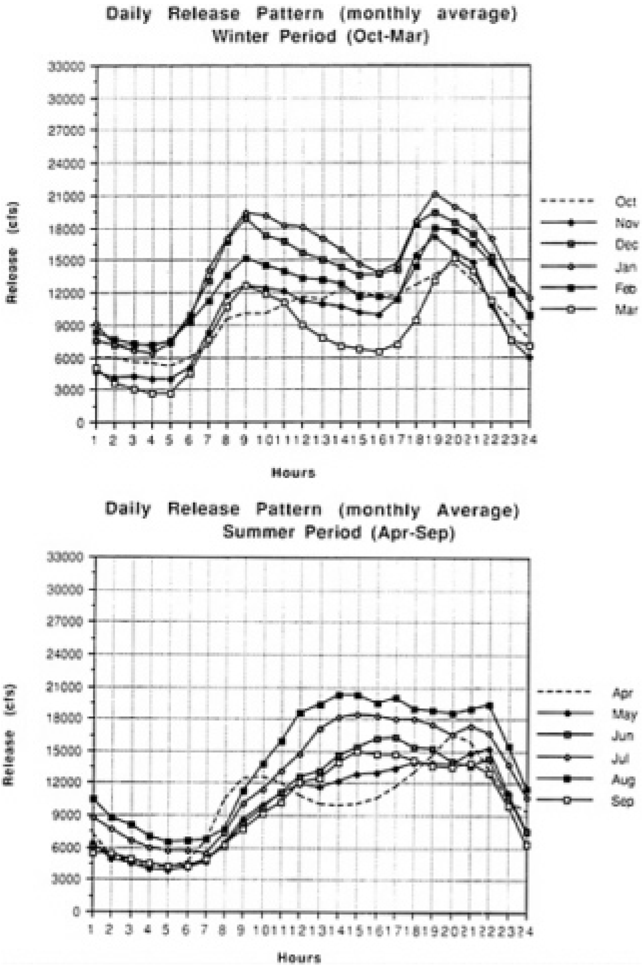

FIGURE 9-7
Hourly average releases each month during 1982.
SOURCE: WAPA, 1982.

perspective of real-time operation, consider Figure 9-8, which shows actual operation for a single weekday (July 29) during a high-demand month of 1982. Figure 9-8 shows actual dam releases, the average releases for peak and off-peak hours, and an assumed load. The hypothetical load must always be greater than the 35% of firm capacity (about 10,700 cfs), and the integral of the area between the dam release line and load represents kilo-watt-hours of fossil fuel purchased during off-peak hours. The firm sales line during peak hours is also drawn arbitrarily. The integral of the area between the dam release line and the firm sales line represents sales on the spot market. This quantity may actually have been zero on this day, indicating that all sales were to firm customers. The water saved at night by buying fossil fuel may be sold to nonfirm or either firm customers or both, and it may be sold on the same day or on any other day. Note that the USBR monthly target imposed on WAPA for July 1982 was apparently 0.66 maf. This can be determined by multiplying the average monthly releases during off-peak hours (7,300 cfs) and peak hours (15,000 cfs) by the frac

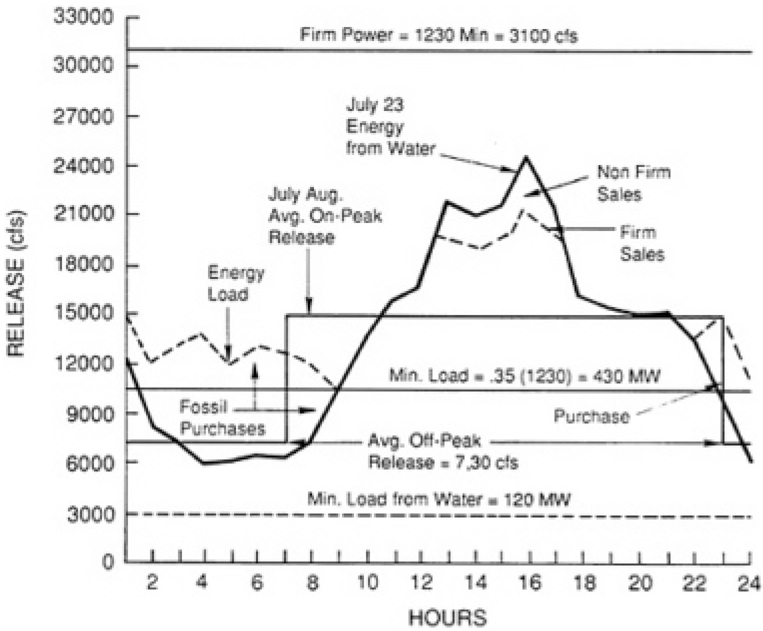

FIGURE 9-8
Daily power releases.
SOURCE: WAPA, 1982.

tion of monthly hours for these two periods (0.52 and 0.48) and multiplying the sum by the number of acre-feet in a cfs month (about 60). The fraction of peak and off-peak hours assumes that weekend and holiday days are all off-peak.

The results of the research flows cost model should be interpreted in relation to differences between the experimental and historic ramping rates. This raises the question, What are the historic ramping rates? The hourly data for all 23 years of operation of GCD were used to develop the following summary of historic ramping rates. The average maximum ramping rates in delta cfs/hour for durations of 1–7 hours are shown in Figure 9-9 for each of the 7 days of the week. Since the data base used contains 24 years of 52 weeks each, there are 1,248 measurements (one for each day of the week) for each quantity shown. The average maximum is therefore obtained by calculating the maximum change in flow rate over the selected duration for 1,248 days and finding the mean. The standard deviations of these

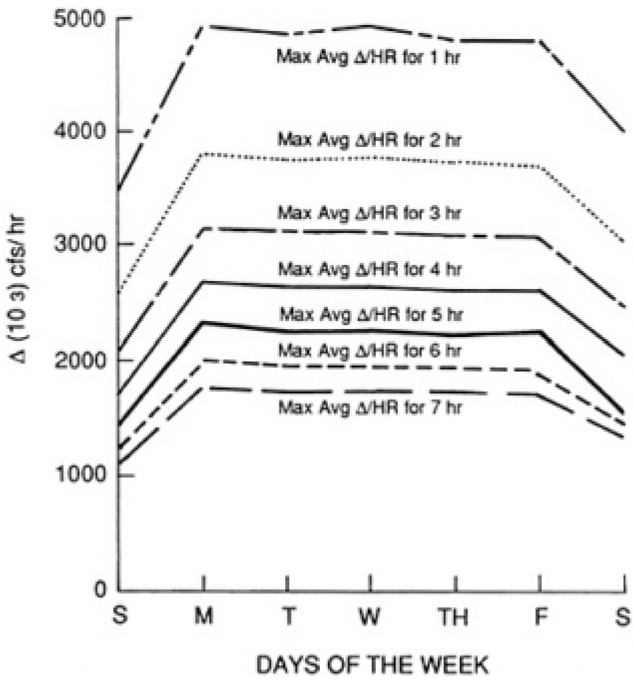

FIGURE 9-9
Summary of historic ramping rates.
SOURCE: Upper Colorado River Commission, 1987.

statistics vary from 2,015 to 2,723 cfs for the 1-hour duration and from 590 to 836 cfs for the 7-hour duration.

The ramping rates selected for research flows were either 3,600 or 7,200 cfs/hour. The 7,200 rate is about 1 standard deviation above the maximum average of the historic record for 1-hour duration, and therefore rates higher than 7,200 have been experienced during about one-sixth of the days of record. The low rate of 3,600 approximates the daily average maximum for 2 hours and is about double the average maximum for 7 hours.

Flows in the Grand Canyon Relative to Dam Releases

A distinction should be made between dam releases and flows through the Grand Canyon. The downstream peaks will be lower and the minimums will be higher than the rates of release from the dam. The USBR has developed a routing model which attempts to predict this relationship at 5 downstream locations: Lee's Ferry, Little Colorado, Grand Canyon gage, National Canyon, and Diamond Creek. The model results estimate that typical peak flows in the Grand Canyon sites are about three-fourths of the peak rates leaving the dam (nine-tenths at Lee's Ferry) and the minimum flows are about double those leaving the dam. The lag Limes between the dam and these locations are of course a function of flow rate (with high flows overtaking low flows), but a decreasing sequence of relatively low flows is estimated to have the following lag times in hours: 3 to Lee's Ferry, 19 to Little Colorado, 29 to Grand Canyon, 44 to National Canyon, and 56 to Diamond Creek. These times seem to differ substantially from those reported in the GCES newsletter as being measured during a dye study in October ~989. During the research flows of 1990-1991, continuous measurements of flow rates at all of these gages should be made to enable testing and improved calibration of the USBR routing model.

Conclusions

1. The GCES II economic impact research team, which is charged with analyzing the economic cost of possible increased minimum releases from Glen Canyon Dam, should use hourly historic data for developing both the generation and load probability distributions. This approach will improve the modeled shapes of both the load pattern and the dam release pattern relative to those used in the WAPA reports to date.
2. The shape of the typical daily release pattern used to represent both the base case and the modified operating policy should include explicitly the ramping between peak and off-peak hours. This will allow analysis of the cost of reduced allowable ramping rates as well as increased minimum

flow rates. The economic impact of ramping rate limits could conceivably be as important as that of minimum flow increases.

3. The role of WAPA's marketing policy of 35% minimum fraction of firm load during off-peak hours, and possible future variations of that requirement (either up or down), should be included in the economic analysis.
4. The question of how much (if any) an increased minimum dam release requirement will change the CRSP firm energy load, in both the near and long terms, should be included in the analysis by the economic research team.
5. Neither the current operating mode of GCD with its large diurnal fluctuations, nor any reasonable modification to the current minimum release criteria will have any impact upon the ability to meet the law of the river.

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10

A Brief History of the Glen Canyon Environmental Studies

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INTRODUCTION

The Glen Canyon Environmental Studies (GCES) and the National Research Council/ Water Science and Technology Board (NRC/WSTB), have been working together since 1986 toward the development of a coordinated and scientifically credible program of research. Over the last day, we have heard a great deal of excellent and important information regarding the Grand Canyon resources that depend on the Colorado River for their lifeblood of continuing existence; much the same way that Las Vegas, Los Angeles, and Phoenix depend on it.

Many different perspectives have been presented on what changes have occurred to the Grand Canyon resources due to Glen Canyon Dam. Over the last 27 years, the changes to the ecosystem of the Grand Canyon have been extensive. The overall objective of this symposium has been to bring together the many pieces of the ecological and economic picture that had not been addressed during the first phase of the GCES program and to identify how they can be applied to the GCES-Phase II. This information will be useful to the scientists and hopefully the decision makers as we develop and implement the GCES Phase II research program. The pathways for successful completion of the scientific effort should build on the information already known and focus on integration of the research and monitoring needs of the future.

Ultimately, the intent of this symposium is to lay the groundwork for the

GCES Integrated Research Plan. This is the plan that Duncan Patten, the GCES researchers, and the scientists have been working on and those studies upon which the GCES Research Flows are structured.

The goals of this paper are to (1) evaluate the use of the GCES scientific information in the Glen Canyon Dam environmental impact statement (EIS) process and (2) evaluate the future use of the GCES data in the management of Glen Canyon Dam and the resources of the Colorado River through the Grand Canyon. This discussion will be developed by focusing on these key areas: (1) the role that the NRC/WSTB has played in the GCES program, (2) identification of how the GCES and GCD-EIS could fit together, and (3) identification of options and challenges to that fit and the role of science in the decision-making process.

As program manager for the GCES, I have been involved with the development, implementation, and use of the scientific information that forms the core of the GCES effort. My responsibility has rested with working with the scientists and researchers to find a means of coming up with answers that could be used by decision makers and also retain the scientific credibility required to withstand the scrutiny of the courts and the scientific community. Management of the program requires a continual balancing of what the decision makers want versus what the researchers are willing to say. Often one finds oneself in a no-win situation between management desires, time, budget, and scientific credibility.

What is the role of science in governmental decision making? The federal and state governments of the United States have a mandated responsibility to the management and protection of our natural and developed resources. These mandated responsibilities often conflict as one office is charged with protection and a sister agency is charged with development. This is especially evident in the management of the ecological, water, and electrical resources of the Colorado River.

As we start to explore these responsibilities and their relationships to the GCES program, it is important that we put into context what credible scientific research is about and why the NRC was brought in to review the GCES program.

NATIONAL RESEACH COUNCIL INVOLVEMENT WITH THE GLEN CANYON ENVIRONMENTAL STUDIES

The GCES program was initiated by the Department of the Interior in December 1982 as a component of the environmental assessment developed for the uprating and rewinding of the eight electrical generators at Glen Canyon Dam. The studies were to be initiated immediately. The uprating and rewinding program was to proceed while the studies focused on the issues associated with Glen Canyon Dam operations. The studies were to focus on a broad range of ecological and recreation issues but were not to address the economic or societal parameters. Limited direction, background information, and boundaries were established for the scientific effort. In addition, limited time was spent on designing studies or exploring the potential for having outside expertise involved.

During the course of the GCES program, the maximum dam release levels were to remain at 31,500 cubic feet per second. In December 1982, few realized the high extremes in water releases that were to come over the next several years.

In 1985, the GCES program organized an interagency trip through the Grand Canyon to discuss the GCES program, the issues that were being explored, and how to integrate the information. That trip allowed for in depth and expansive discussions regarding the initial results of the studies and how that information could be used in a decision environment. From those on-river discussions, it became apparent that an extensive scientific review process would benefit the overall GCES program and would assist the Department of the Interior in its review of the actions to take at the conclusion of the GCES efforts. From those early discussions in October 1985, the groundwork for the NRC/WSTB involvement was laid.

The GCES began active consultation with the NRC/WSTB in December 1985, and by January 1986 we were officially asked to come to Washington to make a presentation at the WSTB meeting.

The presentation in Washington left several of us wondering what we had gotten ourselves into. Harold Sersland, Regional Environmental Officer (Reclamation), Martha Hahn (National Park Service), and I presented an overview of the GCES scientific program to the newly formed WSTB. The WSTB members asked some very insightful and probing questions about the goals and future of the GCES scientific program, and they demanded very distinct answers. Dick Marzolf, with his desire to take on this issue, and an enthusiastic WSTB staff jumped feet first into the NRC/WSTB review process.

Because the GCES program was well under way when the NRC/WSTB became involved, the opportunity to take full advantage of its expertise and wisdom in planning the GCES program was limited. Instead, we focused on four broad objectives:

1. Provide review and advice on the GCES scientific program and provide a general assessment of how well we were achieving our intended goals.
2. Advise on interpretation of information for impact analysis from the technical data developed.
3. Provide advice on the process of identifying the environmental elements for ranking operational alternatives.

4. Extrapolate from the GCES study recommendations to others who may pursue similar environmental studies at other sites in the future.

From those broad objectives, the overall GCES and NRC/WSTB program was formulated.

APPLICATION OF SCIENCE AND RESEARCH TO MANAGEMENT

From the start, the GCES program was between a rock and a hard spot. On one side of the coin, the outside world and natural resource bureaus and agencies looked upon the GCES program as their opportunity to finally have a say in the management of Glen Canyon Dam. To the federal water managers and dam operators, it was a challenge to keep the lid on Pandora's box. A stated goal was to complete the studies in a timely manner and integrate any changes at Glen Canyon into the existing operational criteria.

The challenge for the scientists, considering that we were given limited, often conflicting directions, was to formulate a research program that would address the primary areas of concern, would establish a scientifically credible program, and would determine the actions that could be taken from the data. Balancing science, bureaucratic expectations, opportunities for action, and the limits of the program helped shape the GCES program, often on a day-by-day basis.

Responsibility for completion of the GCES program has always rested with the Bureau of Reclamation. As the entity that has the ultimate control of the water releases from Glen Canyon Dam, Reclamation has the responsibility for any changes that would be made. The GCES program was organized as a multibureau, multiagency cooperative effort utilizing the best scientific resources available. It was the responsibility of these scientists and GCES to focus on three broad tasks: (1) development of the scientific boundaries of the studies, (2) integration of the scientific programs, and (3) development of a conservative scientific approach to the use of the data and subsequent analyses.

Initially, the GCES program was developed around two very broad and limitless objectives, objectives that have resulted in seemingly endless discussions between the constituent groups on intent and boundaries: (1) determine the impacts of the operation of Glen Canyon Dam on the natural and recreation resources of the Grand Canyon, and (2) determine whether there were ways, within existing Colorado River Storage Project mandates and the law of the river, to modify the operations of the dam so as to minimize the impacts downstream.

The GCES scientific team began the overall process with very little institutional direction and even less of an idea of the extent of the effort. (Little previous integrated scientific work had been done, and information avail able on the impacts on other large river systems below dams is limited.) But we muddled through, often by the seat of our pants and very often making things up as we went along. Many research plans had to be modified mid-trip, as the promised flow schedule would change radically in response to upstream or downstream demands. No one could predict the flows, what research could be accomplished, or more importantly, how the information would be used by the decision makers.

The GCES program was not intended to be a long-term affair, beyond the initial 2-year window. In fact, many people within Reclamation and other bureaus and agencies found it highly doubtful that it could acquire any useful information at all.

By the end of 1986, with the review by the NRC/WSTB well under way, a defined GCES scientific program endpoint of December 1987 was selected. The research effort was directed to begin winding down, and the effort refocused on report development and overall study integration.

With the completion of the primary scientific field studies in 1987, a core group of scientists, representing several federal and state offices and private consultants, began the task of assimilating the information into a document that could be used in the decision process. This group of scientists, the Technical Writing Integration Team, spent long hours laboring over the data and the analyses. The result was the "GCES Final Report," backed up by more than 30 published technical reports and many more background documents. The NRC/WSTB completed their review of the individual technical reports and the "GCES Final Reports" and published their findings and recommendations in December 1987 in *River and Dam Management: A Review of the Bureau of Reclamation's Glen Canyon Environmental Studies*.

Transferring the scientific knowledge into management options required the development of a new group of experts, the GCES Executive Review Committee (ERC). The ERC's role was to take the scientific perspective and develop management and policy options for the Department of the Interior. The ERC was composed of policy and management level personnel from the National Park Service, the Fish and Wildlife Service, the Bureau of Reclamation, the Department of the Interior (Office of Environmental Affairs), and the Western Area Power Administration. The GCES program manager served as the liaison between the scientists and as the overall coordinator of the ERC report. After considerable deliberation and identification of management missions and goals, the ERC presented its findings and recommendations in a briefing and in a report to the Department of the Interior.

In June 1988, after considerable deliberation, the Department of the Interior determined that additional information was required before any definitive changes in the operations at Glen Canyon Dam could be considered.

The department directed that additional studies were specifically needed to understand the relationships between fluctuating and low flows and the endangered species, the trout fishery, and the sediment deposits. Additional studies, under the responsibility of the GCES program, were to be conducted on the economic impacts that would result from operational changes at Glen Canyon Dam. The underlying intent was to develop enough information to look at all of the options and impacts. The time frame for the GCES Phase II efforts was not defined, but it was recommended that the studies be carried out under "normal" operations at Glen Canyon Dam, which as defined would take approximately 5 years to complete. The GCES Phase II program was initiated by this directive from the Department of the Interior, and the major constituent groups were asked to participate.

The GCES Interim Technical Integration Team outlined their concerns on the adequacy of program direction and the schedule and recommended that specific research flows be studied, that contracts and agreements be developed and that the services of a senior scientist be acquired. Many of these recommendations built on the intent initially laid out by the NRC/ WSTB final report recommendations. The Interim Technical Integration Team also outlined the questions and areas that they believed could and could not be addressed under the proposed time and flow schedule.

GLEN CANYON ENVIRONMENTAL STUDIES-PHASE II

The GCES Phase II studies were directed by the Department of the Interior to address as many of the NRC/WSTB recommendations as possible. One of the very first that we took on was the issue of hiring a senior scientist to direct the development of an integrated and comprehensive scientific program. Dr. Duncan Patten was chosen to develop a stronger scientific core for the GCES program.

In July 1989, after considerable discussion and public pressure, the Secretary of the Interior directed that an EIS on the operations of Glen Canyon Dam be initiated. With that directive, the GCES program focus changed again, to now become the data base for assessment of the alternative operational and nonoperational options for the overall EIS process. The scientific program was expanded to include the additional concerns to be addressed under the EIS aegis.

The original direction was that the GCES Phase II program would remain on the 5-year timetable. However, in October 1989, the Department of the Interior and the Bureau of Reclamation reset the timetable for completion of the EIS to 24 months. The needs of the scientific program were not considered in that decision.

With the new timetable, the GCES scientific program required considerable overhaul to ensure that what was needed for the EIS could be acquired in the shortened time frame. The scheduling of specific research flows became a scientific necessity.

ECOSYSTEM APPROACH AND INTEGRATION OF THE NAS PHASE I CRITIQUE

The GCES Phase II research efforts are designed to integrate as many of the comments and recommendations developed by the NAS as possible. Those NAS recommendations that related to specific technical perspectives were instituted immediately. This has included the hiring of a senior level scientist and the development of the study program based on an integrated, ecosystems level approach. Additional guidance relating to expansion of the technical studies into the non-market economic and power related studies has also been initiated.

However, there have been several of the NAS recommendations that have not been acted upon. The reasons for that are many and are related to the bureaucratic requirements and administrative hurdles more than a lack of scientific desire to complete. Areas of most frustration and lack of action include: (1) Hiring of the senior Scientist at the Department of the Interior level—this was not achieved. (2) Development of study plans and proposals through an open and public process. Due to the constraints of time the study plans have been developed primarily within the agencies. (3) Inclusion of Lake Powell and Lake Mead into the program. Administrative boundaries have limited our ability to integrate "officially" the ecological effects and impacts of Lake Powell and Lake Mead on the ecosystem of the Colorado River. (4) Development of a full and comprehensive scientific approach. Limits of time, money, personnel and administrative support have restricted what can be done and how it is to be accomplished.

The GCES program continues to build upon the direction provided by the NAS. We believe that a sound and credible scientific approach will best support the administrative decision process. An inherent problem in the "applied" scientific approach is that constraints and implied administrative boundaries limit the application of the best intent.

DEVELOPMENT PROBLEMS FOR THE GLEN CANYON ENVIRONMENTAL STUDIES PROGRAM

Despite our best intentions, we find ourselves today still faced with some of the same, very difficult problems in completing the GCES Phase II program and ultimately developing a credible EIS document. These include:

1. Development of a definitive, scientifically driven, timetable.
2. Acceptance that not all of the questions will be answered within the

short EIS timetable. Additional research and long-term monitoring will be required.

3. Development of clear study boundaries. Politically the lines have been drawn but from an ecosystem perspective the boundaries are far more considerable.
4. Development of adequate support and staffing within all cooperating entities and the GCES.
5. Development of the process whereby the scientists can voice their scientific findings and thereby ensure that open and credible scientific analyses and process occur.

INTEGRATING THE GLEN CANYON ENVIRONMENTAL STUDIES PROGRAM WITH THE GLEN CANYON DAM ENVIRONMENTAL IMPACT STATEMENT

The Glen Canyon Dam EIS is a process dictated by the rules and regulations of the National Environmental Protection Act (NEPA), with guidance defined by the Council on Environmental Quality. The EIS is a process; it does not guarantee a change, or that all considerations will be given equal weight in the decision process. NEPA is a *only a process* . The quality and equity of that process are largely dictated by the quality of the data base and the way that the data and analyses are used in the decision process. The necessity for a strong and credible GCES scientific program has never been more critical and more hotly debated.

The EIS process is important because it allows all of the issues to at least be stated. The public and the constituent groups can be a party to the equity process if they participate actively.

The Glen Canyon Dam-Environmental Impact Statement (GCD-EIS) is directed to evaluate the impacts of the operation of Glen Canyon Dam on the natural, recreational, water and electrical resources of the Colorado River. The EIS process and the GCES program are to be integrated together with the GCES scientific results providing the technical information for evaluation of the alternatives being developed through the EIS process.

The GCD-EIS is indirectly establishing the administrative and scientific boundaries to the GCES program. Additionally, the EIS process requires the development and/or collection of non-ecosystem related, technical information. Studies that have been added to the GCES program in addition to those previously identified in the ecosystem approach include cultural resource studies, archeological studies, endangered species studies, Fish and Wildlife Coordination Act studies, and extensive coordination with the Native American groups.

The boundaries and timing of the GCES program are directly related to the GCD-EIS requirements. If conducted under a strict scientific approach the GCES Phase II efforts would be conducted over a five to six-year time frame. This would allow for development of adequate study plans, and adequate review and integration of the scientific effort. Currently, the GCD-EIS is on a schedule that requires *completion* by December 1993. This means that the majority of the science must be completed by January 1992. Ecosystem processes don't work that quickly or follow administrative dictates.

The goal of the GCES program is to develop a technically sound and scientifically credible research approach integrating all of the specific studies into a consolidated and coordinated effort. The GCES program will develop the technical data base that can be used to evaluate the impacts associated with GCD-EIS alternatives that relate to operational changes at Glen Canyon Dam. Response relationships and risk assessments will form the underlying precepts for this evaluation. Limited information will be collected to evaluate specific structural alternatives. A major problem may exist in the future as administrative expectations clash with ecosystem processes. In the past, the issues surrounding maintenance of the ecosystem in the Colorado River has not provided a successful merger of society and the environment.

Can the GCES program guarantee a sound and credible EIS decision? NO!! The best that we can do is provide a credible and sound scientific approach and analyses that will provide the decision makers and the public with the information needed to make the decisions. It is our responsibility as scientists and researchers to provide the best we can with all of the tools at our disposal; that includes the use of in-house and out-of-house expertise, ourselves, the NRC and the senior scientist.

OPTIONS FOR THE FUTURE

I have been asked many times by non-Reclamation people, What would be best for the resources of the Grand Canyon? What can we do to help the resources? My reply is this: Support the science. GCES must provide the best scientific basis that it can for the decision makers. We will do no one, least of all the resources of the Grand Canyon, any good to have this effort end up in a draw or in court. While many bureaucrats and lawyers may look upon that view as a way to ensure job security, the real losers under any other approach would be the resources of the Grand Canyon.

Who bears the blame for a non-answer? While the responsibility could be laid on any number of entities, I fear that the scientific community would be the likely scapegoat. Everyone is looking for that "one ultimate answer," and quite frankly there isn't one. The politicians and bureaucrats can maneuver their way out from under the scrutiny, but ultimately the public will be looking for a fall guy. The blame for the lack of data and answers will likely fall on the least protected entity, the scientists.

Therefore, what options and alternatives should we be looking at? Is there one solution or path that should be followed? What decision process can best provide the information and balance necessary to help the resources yet maintain scientific credibility and our societal and legal obligations?

I think that there is a set of solutions. Very briefly, the solutions at Glen Canyon Dam could follow a three-phase approach:

Phase I	The first phase would involve implementation of operational changes at Glen Canyon Dam as a result of the NEPA process and the GCES program. The majority of any operations changes could be made within the context of the existing law of the river and the operational criteria for Glen Canyon Dam. This immediate action probably could be done with a minimal amount of legal proceedings. I further suggest that these operational alternatives be structured around the way the dam and river system is operated today—namely, around the annual flow volume projections. Additionally, a set of defined environmental criteria with priorities for implementation must be developed. A set of operational and environmental criteria for low, average, and high water years would be developed and negotiated by a multidisciplinary management group each year. The problem with solely implementing operational changes is that it will only serve to minimize the impacts of the day, not alleviate them and certainly not return the Grand Canyon ecosystem to conditions similar to those that existed at the time of the dam closure.
Phase II	The second phase would be to develop a long-term research and monitoring program that continues after GCES is completed to further study and monitor the ecosystem relationships and progress vis-à-vis operations. If necessary, the operations would be fine-tuned if additional impacts are identified. Ecosystem evaluation could be built into the existing annual and/or five year review program defined for the secretarial hydrologic review of the Colorado River operations.
Phase III	Third and perhaps most intellectually challenging would be the development of an ecosystem restoration program, a program that would focus on working in concert with the natural pro

cesses of Grand Canyon to restore parts of the ecosystem that have been lost or severely affected by Glen Canyon Dam. As portions of the ecosystem are restored, the resiliency of the ecosystem may be increased and the levels of operational impacts could be reassessed.

Forms of ecological restoration could range from sediment augmentation to exotic species eradication. We are limited only by our understanding of the natural and manmade processes and our desire to explore the boundaries of the knowledge of ecosystem processes.

THE CHALLENGES THA LAY AHEAD

The challenges for more enlightened management of the resources of the Colorado River are many. Completion of the GCES program and the Glen Canyon Dam EIS is going to take a great deal of hard work but is only one step in many that are required if we are to consider ourselves wise stewards of the resources. Dealing with the internal politics and conflicting mandates that drive this diverse process is not going to get any easier.

To achieve a credible scientific and EIS process, many groups must shoulder their share of the responsibility. These responsibilities are not to be treated lightly.

The Bureau of Reclamation must bear the primary responsibility of putting together the teams necessary to get the job done. This will necessitate a multibureau-multiagency approach that is open to the scrutiny of all. This effort also includes providing the overall coordination, budget, and staffing necessary to accomplish the program goals.

The National Park Service, Fish and Wildlife Service, Arizona Game and Fish Department, and the other state and federal resource agencies must bear the responsibility for ensuring that their resources and concerns are voiced and provide support in all phases of the GCES and EIS programs.

The Department of the Interior must bear the responsibility of maintaining balance and making the ultimate decision. The department must ensure that all bureaus' and agencies' perspectives are voiced, that a credible and open decision process is developed, and that a commitment is made to the future of the resources of the Colorado River.

Constituent groups and the public must bear the responsibility of making sure that we are doing our job to the maximum extent possible and not getting lazy in either our approach or our responsibility. Additionally, they must be willing to help avoid the common belief of today—that the court or Congress must make the decisions.

The NRC/WSTB must bear the responsibility for ensuring that we are doing our scientific best. No second-best efforts should be tolerated. Sound scientific direction and support for a credible scientific process must be given.

The scientists must bear the responsibility for developing the most credible scientific product that they can within the boundaries of the studies—a scientific program that can stand the test of time and the courts. Demand and provide the best.

SUMMARY AND CLOSURE

The GCES program has been an evolving process. When I reflect on the beginnings of GCES, I am reminded of a correlation that Wallace Stegner made to Major John Wesley Powell in the book *Beyond the Hundredth Meridian*. Mr. Stegner referred to Major Powell's scientific and professional program as following a "corkscrew path of progress." In many ways the GCES program has followed a similar, convoluted path.

We seem to have followed a path strewn with change and modification, often on the run. "Chaos" seems to have become a law of nature and "order" a dream of us all. Do I see an endpoint to the GCES? The answer is yes. Will the answer mean anything when we are finished? We should all be looking to ourselves for that answer. I hope that when we get through with this effort, we will have gained for the resources.

As the GCES Phase II program enters into the support of the EIS program, undoubtedly changes will occur—changes based on the science and changes based on the politics and bureaucracy of the system in which we function.

The GCES has strived from its inception to represent a credible and scientifically driven process. Often the balance between the expectations of the managers and the reality of the science do not mix. In many venues, science and data are viewed as a threat—a threat to the norm and to the way that decisions have been made in the past. It is inevitable that the science and the scientists of the GCES program will be questioned and perhaps even attacked for their efforts and results. Perhaps a quote from Abraham Lincoln, modified to reflect the GCES perspective, states it best:

> If we were to read, much less answer, all the attacks made on us, this shop might as well be closed for any other business. We do the very best we know how, the very best we can, and we mean to keep doing so until the end. If the end brings us out all right, what is said against us won't amount to anything. If the end brings us out wrong, then all the angels swearing we were right would make no difference.

The role of scientists in the bureaucratic decision-making environment is indeed tenuous as they try to balance the scientific credibility of the profession against the wants and desires of management. That balance is often strewn with the harsh reminders that conflict continues between science and bureaucracy. Scientific knowledge is an enabling power to do either good or bad but does not carry a list of instructions on how to use it. The scientific knowledge being developed through the GCES program will be a body of statements with varying degrees of certainty. Some issues will remain unsure and unresolvable, some issues will be nearly resolved, but no answer will be absolutely certain. The best that can happen is to make the best estimates and apply it to the issues of concern. The challenge is to develop an integrated, adaptive experimental design that will permit clear separation of the effects of as many of the impacts as possible so that a sensible balance of scientific information, management requirements and administrative mandates can be developed.

The Grand Canyon will be here long after we have departed this earth. However, we have a responsibility to minimize the impact of our stay on so precious a resource. As scientists, our role may change but our responsibility to stand up for a credible scientific cannot waver.

11

Glen Canyon Environmental Studies Research Program: Past, Present and Future

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ABSTRACT: The present research program within the Grand Canyon is a result of inadequacies of the initial Glen Canyon Environmental Studies. These inadequacies were partially due to poor planning and research design, but also to the high water conditions during the research period. The results of the initial phase, GCES I, were reviewed by a National Research Council committee which recommended, along with the Glen Canyon Environmental Studies Executive Review Committee, that further studies be done on the effects of dam operations on the Canyon resources. This led to establishment of GCES II which has gone through an iterative process to develop testable hypotheses on the effects of dam operations and other activities in the Canyon. Experimental designs are being developed for research, and controlled research discharges from the dam scheduled for the next 2 years. This short-term research program has been developed to address the data needs of the EIS which will select a dam operations alternative for the future. It is recognized that this short-term research program will not thoroughly explain the functions and responses of resources within the Canyon, and that a long-term research and monitoring program is necessary for evaluation of the EIS-selected alternative.

BACKGROUND: GLEN CANYON ENVIRONMENTAL STUDIES I, 1982-1987

The Glen Canyon Environmental Studies (GCES I) were initiated in 1982 in response to potential changes in the Bureau of Reclamation's manage ment of water flowing in the Colorado River through Glen Canyon Dam because of upgrading of the dam's eight generators. The early history of the Bureau was one of water storage for control of down stream flows, primarily for irrigation. However, environmental concerns arising in the 1970s raised questions about the Bureau's water management decisions, for example, those dealing with operations of Glen Canyon Dam. Thus the Bureau established the Glen Canyon Environmental Studies to develop data that could be used to make decisions on the operating criteria of the dam and the environmental and legal requirements related to management of the Colorado River.

GCES I, as a multi-agency effort, produced 33 technical reports based on 4–5 years of study. These reports were integrated into a composite final report (USDI 1988a) that addressed the question of how much impact the present operations of Glen Canyon Dam had on the Grand Canyon ecosystem, including downstream human activities. The executive summaries of the technical reports were also combined into a single volume for ease of reference (USDI, 1988b). The technical reports were presented in four major groups, sediment, biology, recreation, and dam operations. The information from each of these groups presented various levels of impact on resources resulting from dam operations. GCES I was able to make a few significant statements. These were:

- Some aspects of the operation of Glen Canyon Dam have substantial adverse effects on downstream environmental and recreational resources.
- Flood releases cause damage to beaches and terrestrial resources. Under current operations of the dam and lake storage, flood releases will occur in about one of every four years.
- Fluctuating releases primarily affect recreation and aquatic resources.
- Modified operations could protect or enhance most resources.

In the end, it was realized that GCES I research had occurred during an abnormal high water period and that the understanding of the relationships between dam operations and downstream resources were incomplete.

DEVELOPMENT OF GLEN CANYON ENVIRONMENTAL STUDIES II RESEARCH PROGRAM

In 1987, when GCES I had ended, there was concern that the research program had not developed the information base necessary to evaluate the operations of Glen Canyon Dam. Although the Glen Canyon Environmental Studies Executive Review Committee had used the results of GCES I to indicate that Glen Canyon Dam was causing an impact downstream, it did not totally endorse some of the conclusions of GCES I and thought that more research was necessary, especially on impacts of low-fluctuating flows, endangered species, and power/recreation economics (USDI 1988c). The request for more research under normal dam operating conditions for these limited areas was supported by the Assistant Secretaries of Interior for Water and Science, and Fish, Wildlife and Parks in June 1988.

At the time GCES I was being consolidated into a final report, a committee of the National Research Council's, Water Science and Technology Board was funded by GCES I to review the whole program from research initiation through the final integrated report. The report from this committee was completed at the same time as the Executive Review Committee's report to the Secretary of Interior. The NRC review and recommendations were a critical input to the future development of a research program on the impacts of the operations of Glen Canyon Dam.

REVIEW OF GCES I BY THE NRC COMMITTEE

The 1986–1987 review of GCES I by the NRC, Water Science and Technology Board, Glen Canyon Environmental Studies Committee (National Research Council, 1987) addressed inadequacies of the research program, but also pointed out that GCES I had produced much valuable data that would be useful to continued studies of the Grand Canyon ecosystem and the operations of Glen Canyon Dam. Some of the major criticisms presented by the NRC committee include: (1) insufficient attention to early planning, review of existing knowledge, and careful articulation of objectives, (2) lack of distinction between science and management of the project, with a need for a senior scientist and scientific oversight group established at the beginning of the studies, (3) lack of soliciting the best scientific talent to do the research, (4) inadequate consideration of economic consequences of various management options, and (5) uncertain conversion of research results into management options. The committee also stated that ecological understanding of the system is paramount to making defendable management decisions, the understanding in this case requiring a sustained research effort because the river is in disequilibrium and operational decisions will require continuous monitoring to ensure the desired environmental effects are being achieved.

Other pertinent points raised by the NRC committee were presented under the various resources being studied in the Canyon. These include:

- For aquatic resources: evaluate the quality of water at various potential release levels in Lake Powell, include algal and invertebrate productivity in future studies, perform focused studies on sediment movement, and develop process-oriented models to understand sediments, water temperatures, nutrient concentrations, and economic and power production.
- For terrestrial biology: establish links to river productivity, and anticipate heterogeneity and match methods to temporal and spatial scales.

- For sediment and hydrology: study tributary processes, include empirical approaches and modelling in hydrological studies, link sediment studies to hydrological and biological monitoring, and institute geomorphic studies to supplement hydraulic studies.
- For recreation: clarify cost/benefit tradeoffs between power generation and recreation, broaden recreational constituencies, and avoid use of hypothetical flows.
- For operations: initiate a feasibility study of changes in dam operations and non-operation alternatives, and consider all management options.

INITIAL INTEGRATION PHASE OF GCES II

If GCES II was going to contribute to our understanding of the Grand Canyon system, it had to develop a program that regarded the system as an integrated whole, a point emphasized by the NRC committee. For example, beach or sand bar aggradation or degradation is not only important as part of a sediment dynamics study in the canyon, but it also is associated with availability of backwaters for fish recruitment, or beaches for recreational camping. The necessity of incorporating all of the activities and resources in a comprehensive research plan required some form of integration of researchers from the various disciplines studying the Grand Canyon or other similar large river systems.

In July of 1989, over thirty five scientists and resource managers took a 2-week river trip through the Canyon with the explicit purpose of developing research needs for better understanding the Canyons ecological processes and the human activities that impact and respond to these processes. Working within the actual geographical setting enhanced the interchange among the participants. There were those who came on the trip to espouse a single concept or to protect a resource or preconceived idea. Fortunately, the grandeur of the Canyon opened most minds and allowed a balanced exchange amongst individuals from different backgrounds.

There were two goals of this river trip. The first was to develop research questions by discipline, for example, what are the processes that control eddy dynamics? The second was to have each discipline indicate the information it might need from another discipline for a better understanding of processes and responses within its area of interest.

By August 1989 a first draft research program had been developed. This was the beginning of an iterative process with the final goal being a definitive research program with hypotheses and research plans.

The August draft research program was considered too broad by most participants. Too broad in the sense that it addressed most researchable problems in the Canyon and was not specifically related to understanding the impacts of the operations of Glen Canyon Dam. Some participants, however, thought the August draft could have gone farther toward a total ecosystem study of the Canyon based on the concept that in order to understand the impacts, the total system should be thoroughly understood.

The initial research program for GCES II gave structure to identifying the research needs. This was partitioned into three parts: (1) identification and understanding of controlling variables within the system, (2) identification of characteristics for crucial habitats of significant (high priority) resources or resource uses, and (3) understanding the magnitude of the influence of the controlling variables, in static or changing modes on the significant resources or uses. Research guidelines for GCES II were established at this point. These included (1) problem identification, (2) literature search, (3) problem refinement, (4) research design, (5) research and analysis, and (6) monitoring.

The controlling variables were divided between those that are regulated directly by the dam and its operations, and those that are regulated by other factors in addition to dam operations. Dam dependent variables were such factors as flow volume, flow fluctuations, ramping rates, and water quality and temperature. Variables not associated directly with dam operations were such factors as canyon geomorphology, sediment input and dynamics, vegetation dynamics, nutrient dynamics, as well as anthropogenic variables such as recreational activities.

Significant resources for which crucial habitat or environmental requirements need to be identified for research needs included: fish (exotic and native, especially endangered species), aquatic food base, terrestrial vegetation, wildlife (especially threatened and endangered species), recreation, cultural resources, water storage, and power production.

By expanding on the definitions of controlling variables and resource requirements, information gaps were identified that would lead to research needs. For example, for the dam-dependent variable "flow," the relationship between the flow from the dam and flows at different points downstream are unknown, or for the non-dam variable "sediment input," the contribution of sediment from the many tributaries feeding into the Grand Canyon is unknown. Examples of gaps for resource requirements are: for fish, habitat requirements for life stages and reproduction; or for cultural resources, requirements for stability of archaeological sites near or below the high-water line.

The final phase of the first research program presentation was an integration of controlling and response variables. This took the form of (1) interaction among controlling variables such as flow and sediment dynamics, and (2) resource response to controlling variables, such as fish habitat as a function of flows.

After review of the first draft of the GCES II research program, it was necessary to condense the program to points that might be useful in decision making in the managing the dam as well as other resources in the Canyon. This became a necessity because decisions on dam operations were now tied to an EIS, as of August 1989, and the time frame for information gathering was initially set at a 2-year limit, a major reduction over an earlier, 4-plus-year limit. To convince decision makers that many of the resources and processes presented in the first draft of the research program were part of decision making, that is, they connected the controlling variables to the crucial resource responses, a complex system diagram was prepared (Figure 11-1) showing the various steps and processes between an input or control variable and the desired state of a crucial variable. After reviewing this figure, it becomes obvious that 2 years or less is an insufficient time frame to critically evaluate, through legitimate research, all responses between input (controlling variables) and the ultimate state of resource or use.

At this point, the Glen Canyon Environmental Studies research program had reached a stage that required development of a double pronged approach. There was a need for a short-term research program that would address the problems identified in the development of the initial research program in order to achieve a data base that could be used to evaluate the environmental consequences of the EIS alternatives. There was also a need to develop a long-term research and monitoring program to enable a more thorough development of ecosystem process models and to initiate a monitoring program that would be used to evaluate the dam operation alternative selected through the EIS process. This long-term program is essential to the success of the studies within the Grand Canyon, because the time necessary to gain a high degree of confidence in the research models and results is much greater than the time allotted for the short-term component of the research program (Figure 11-2). This does not mean that the short-term research program should have been abandoned, but that our confidence in the results from the short-term program will improve with the addition, over time, of more information.

DEVELOPMENT OF SHORT-TERM RESEARCH HYPOTHESES AND EXPERIMENTAL DESIGNS

The next step in development of the short-term research program was development of short-term research questions that would lead to hypotheses, again using an iterative process among Grand Canyon researchers and resource managers. These questions were related to general issues dealing with operations and management of Glen Canyon Dam and other resources, a condensation of the control and response variables identified in an earlier iteration of the research program. The general headings of these issues were: (1) Effects of Dam Operations, (2) Effects of Recreation, (3) Effects of Economic Balances, and (4) Potential Future Mitigation Alternatives in Addition to Modification of Discharge Criteria.

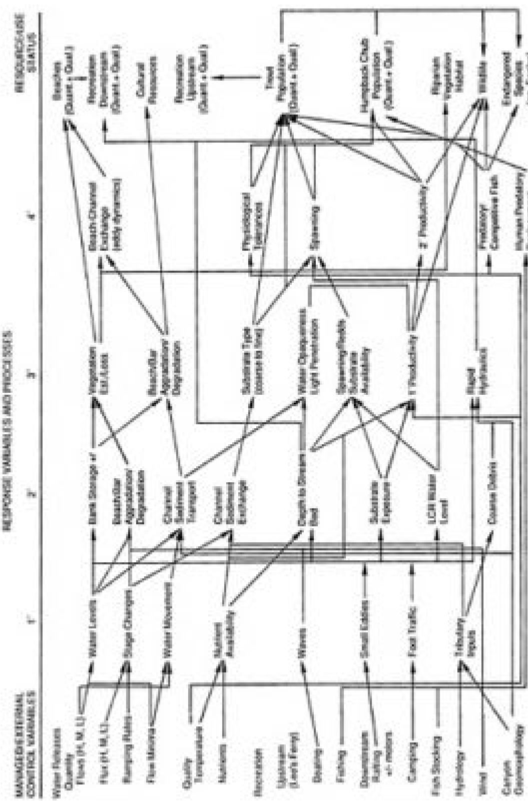

FIGURE 11-1
Interrelationships and Stepwise Connecting Response Variables and Process Between Controlling Variables and Canyon Resource and Use Status.

```
                          1990   1991   1992   1993   1994   1995   1996--
____________________/______/______/______/______/______/______/______/__

Flow Routing Model   - -/-----------X--------------- - - - - - - -
     (USGS)

Sediment Transport   - -/-----------?-----------X------------------
Model (USGS)

Eddy Dynamics           /-----------?---------------X---------------
Model (USGS)

Beach Erosion           /----------(X)---------X------------- - - -
Models (NPS)

Beach Surveys        ---------------?-----------------------------
  (USGS)

Trophic Dynamics     - -/----------(X)----------X------------------
Models (AGF,USGS)

Trout Stranding      ---------------X - - - - - - - - -
  (AGF)

Trout Population     ---------------X - - - - - - - - -
Dynamics (AGF)

Eagle/Trout          ---------------X - - - - - - - - -
Dynamics (BR,AGF)

Humpback Chub        ---------------?---------------X
Conserv. Meas.
(FWS, AGF, BR)

Cultural Resources   --------------(X)--------------------- - - - -
Responses

Recreation Response ----------------X- - - - - -
and Impact Models

Lees Ferry Angler    ---------------X
Access (BR subcont.)

Economic Models      ---------------X
  (BR subcont.)

                          1990   1991   1992   1993   1994   1995   1996--
____________________/______/______/______/______/______/______/______/__

Mitigation

No change alternat. - - - - - - - X
Evaluation

Variable intake      - - - - - - - ?
Structure

Reregulation Dam     - - - - - - - ?

Beach Stabiliz.      - - - - - - - ?

Sediment Augment.    - - - - - - - ?

/ = research initiated
- - - - research ongoing or continued as monitoring
------- intensive research program
X = data and analysis at stage to be useful to EIS, ()=incomplete
? = data questionable whether useful to EIS
```

FIGURE 11-2
Anticipated research schedule and data usability.

The following listing of the short-term research questions (Table 11-1) were developed based on general justification and information needs statements. Research proposals addressing these questions have been prepared by scientists from different agencies, for example, US Geological Survey, National Park Service, Arizona Game and Fish Department, and the Bureau of Reclamation. Some of the economic and endangered fish species research will be done by non-agency scientists through development of proposals responding to Bureau of Reclamation "Request for Proposals" (RFPs).

DEVELOPMENT OF CONTROLLED RESEARCH DISCHARGES FROM GLEN CANYON DAM

Answering the questions and developing response curves and models for the resources in the Canyon require conditions more controlled than the widely fluctuating daily (and seasonally) discharge flows from Glen Canyon Dam. Controlled research discharge flows are an obvious necessity. The duration of the controlled discharges should be sufficient for the system to reach an equilibrium with the discharge. A compromise was made to use a 2-week period, although most scientists agreed that a 4-week period was preferable. A dendrogram was used to determine the minimum number of research discharges (Figure 11-3). These were then placed into a schedule to satisfy downstream water release requirements, and recreation and power network considerations (Figure 11-4). The research discharges included not only controlled regular fluctuations, but also constant discharge

flows (with volumes equivalent to fluctuating discharges), and normal operations fluctuating discharges (based on the same time period from 1989). The only replication of controlled discharges are the first two in July 1990 and July 1991 (see Figure 11-4). If three replications were run for each controlled discharge, the duration for each was increased to 4 weeks, and additional discharges were selected to better test all variables, the research discharge period would last approximately 18 years. This is obviously unacceptable to all concerned. The compromise, for the meantime, has been a composite period of approximately 6 months of controlled discharges. This, perhaps, is erring on the short side. Results from the research undertaken during the controlled discharges will be evaluated with this in mind.

DEVELOPMENT OF LONG-TERM RESEARCH AND MONITORING NEEDS

Any short-term study of an ecosystem as complex as the Grand Canyon is bound to be a failure if the research is viewed as the final answer to understanding the system. The short-term study explained above was developed primarily to address potential EIS alternatives, not to fully under

TABLE 11-1 Outline of Short-term Research Questions for Analyzing Resource Responses.

I. Effects of Dam Operations

A. Effects of the Magnitude of Daily Discharge Fluctuations, Minimum Discharges, and Rate of Change (Ramping) of Fluctuating Discharges.

Q-1.1. How significant are discharge fluctuations, minimum discharge and ramping in the degradation or aggradation of beaches?

Q-2.1. Do discharge fluctuations, differences in minimum discharges, or different rates of change in daily discharges (ramping rates) interact with other uses and components of the Canyon to affect rates of sediment degradation?

Q-2.1a. What is the relationship between the effects of recreational use of beaches and the magnitude in daily discharge fluctuations, daily discharge minima, or daily ramping rates?

Q-2.1b. What is the relationship between the role of vegetation as a beach stabilizer and the magnitude of daily discharge fluctuations?

Q-3.1. How do daily discharge fluctuations, minimum discharges or ramping rates influence the amount of sediment stored in or transported in the Canyon system?

Q-4.1. How do discharge fluctuations, minimum discharges and rates of change of fluctuating discharges affect trout?

Q-4.1a. What is the relationship between the rate of stranding of trout and the magnitude of discharge fluctuations, minimum discharges, or the ramping rates?

Q-4.1b. What is the relationship between behavioral activity of rainbow trout and the magnitude of daily discharge fluctuations, daily minimum discharges and ramping rates?

Q-5.1. How do discharge fluctuations, minimum discharges and rates of change of fluctuating discharges affect foraging success of wintering bald eagles?

Q-5.1a. What is the relationship between trout availability, trout access, bald eagle presence, bald eagle abundance or bald eagle foraging success in the mainstream or Nankoweap Creek and the magnitude of daily discharges?

Q-6.1. How do discharge fluctuations and rates of change in fluctuating discharges affect the population dynamics (including short-term abundance of early life stages and potential predation relationships) of native (especially the humpback chub) and introduced fish species in the mainstem Colorado, including mainstem backwaters and the confluence of the Little Colorado?

Q-7.1. How are water quality (nutrient availability and other characteristics), stream productivity (of algae and macroinvertebrates), and import-export rates or organic matter to and from the Lee's Ferry reach influenced by the magnitude of discharge fluctuations, and the ramping rates?

Q-8.1. How are recreational variables (angler safety and rafting safety, satisfaction, experiential quality and economics) influenced by the magnitude of seasonal or daily discharge fluctuations, minimum discharges or the ramping rates?

Q-9.1. Are there sufficient camping beaches during maximum normal operations discharges from Glen Canyon Dam (i.e., 31,500 or 33,200 cfs) to satisfy the needs of the recreational rafting community based on the NPS acceptable carrying capacity of the Grand Canyon system?

Q-10.1. Do dam operations (e.g., magnitude of stage, magnitude of discharge fluctuations and/or ramping rates) affect the stability of cultural resource sites along the river in the Grand Canyon?

II. Effects of Recreation.

A. Effects of Fishing Activities.

Q-11.1. Does fishing activity, including boating, in the Lee's Ferry reach affect other Canyon resources?

Q-11.1a. Does fishing activity, including boating, affect beach stability, especially in the Lee's Ferry reach?
Q-11.1b. What is the relationship between the trout population of the Lee's Ferry reach and fishing activities, especially catch and release or keep relationships?
B. Effects of rafting and Camping Activities.
Q-12.1. How does rafting and camping affect other Canyon resources, especially the sediment volume of beaches?
III. Effects of Economic Balances.
A. Power Economics.
Q-13.1. If creating a more stable environment in the Canyon below Glen Canyon Dam requires changes in power operations, what is the economic impact of these changes?
B. Recreational Economics.
Q-14.1. Are the economic benefits of downstream recreational activities as well as associated tourism services (e.g., lodging, airlines, restaurants, etc.) affected by operations of Glen Canyon Dam?
C. Non-use Economics.
Q-15.1. Are there any non-use benefits that are attributable to the maintenance of a stable environment in the Canyon below Glen Canyon Dam and if so would these values be affected by changes in dam operations?
IV. Potential Future Mitigation Alternatives in Addition to Modification of Discharge Criteria.
A. Effects of "No Change" Alternative.
Q-16.1. Are there any greater economic or environmental costs to the "no change" alternative if compared to the other alternatives?
B. Effects of Variable Intake Structures
Q-17.1. If a variable intake structure is used on Glen Canyon Dam, what will be the effects of intake at various levels on the downstream system?
C. Effects of A Reregulation Dam.
Q-18.1. If a regulation dam were constructed in the Canyon some where between Glen Canyon Dam and Lee's Ferry, what would be the effects of the discharges from this dam on the downstream system?
Q-18.2. What would be the impact of a reregulation dam on the Lee's Ferry reach if it is constructed in this reach?
D. Effects of Beach Protection Devices.
Q-19.1. Is it possible to mitigate the degradation of camping beaches in the Canyon due to dam operations using beach protection devices?
E. Effects of Sediment Augmentation.
No questions have been developed until methodology is identified.

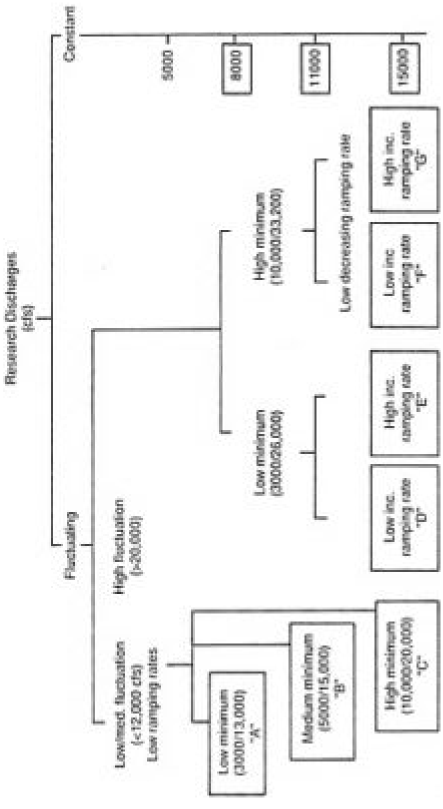

FIGURE 11-3
Dendrogram of Research Discharges. Fluctuating Discharges Have Approximately the Same Volume as Constant Discharges on the Same Level.

stand all of the processes going on within the Canyon. As a result, it has limitations, of which one of the most important may be misleading interpretation of data. This can be avoided only if those doing the interpretation recognize the limitation and place a wide band of uncertainty around their conclusions.

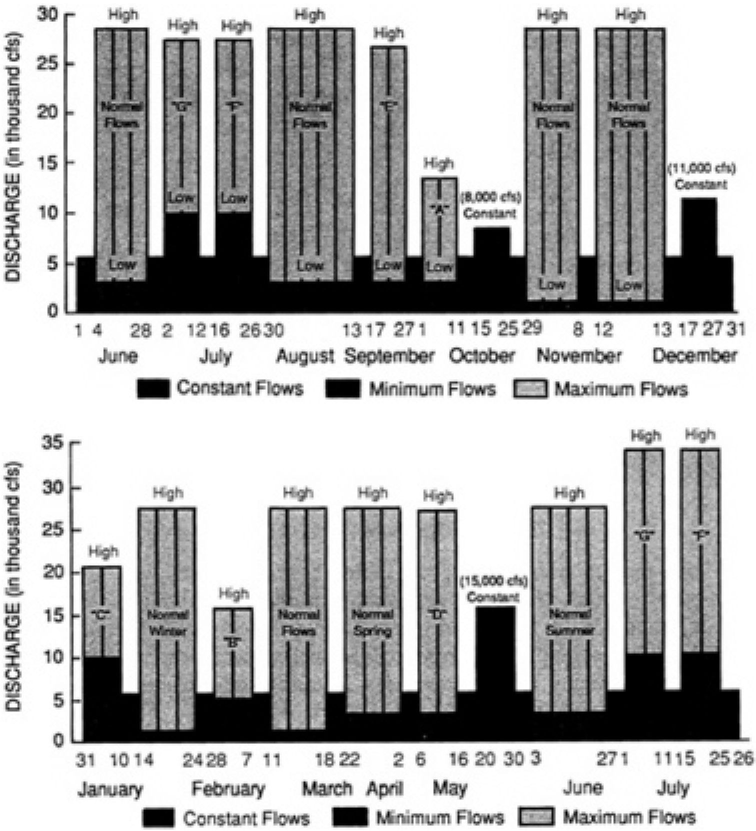

FIGURE 11-4
Research discharge flow schedules for 1990 and 1991.

EXPANSION OF THE SHORT-TERM RESEARCH PROGRAM

To ensure an adequate understanding of the Grand Canyon ecosystem, the short-term research program must be continued in those areas for which long-term data is essential. Models and response curves can be adequately developed for some of the resources in a relatively short period of time, for example, some of the economic models and recreational responses. Models of other processes, such as sediment transport, eddy dynamics, and hump-back chub population dynamics, require a much longer period of data collection than that allotted under the short-term research program, even with controlled, research discharges from the dam. The short-term research data, along with those data generated under GCES I, can only be used, in areas where long-term data are needed, to guide decision making in the EIS process. This does not mean these data will not be useful, they will be useful with limitations.

The need for an expanded research program can clearly be seen in Figure 11-2 which shows estimates of the time needed to generate useful information for a thorough understanding of the Canyon system. This information will be a necessary input into the understanding of the data generated from a long-term monitoring program, a program essential to evaluating the accuracy of the EIS decision-making process.

LONG-TERM MONITORING

A long-term monitoring program should be started along with the present short-term research program and should continue, along with the long-term research program, for some time after completion of the EIS. Monitoring is used to determine the state of resources as well as their response to existing conditions. Changes in the state of a resource indicates a beneficial or detrimental response to controlling variables, such as dam operations. It is the understanding of these changes for which the short and long term research data will be used.

The long-term monitoring program should be organized in such a way as to assure valid determination of changes taking place in the Canyon. This means a regular schedule of measurements of both the sensitive and non-sensitive resources. Some resources, such as camping beaches, should be measured at least twice a year, while others, such as trout spawning and stranding, might be measured just during that season when the response is greatest. The resources to be monitored, as well as the timing and location of monitoring, should be determined from data collected during GCES I, GCES II and the long-term extension of the short-term GCES II studies. However, monitoring should not wait until all crucial resources are identified and thoroughly understood or else some of these resources may be permanently degraded or lost from the Canyon.

CONCLUSIONS

The research program that has been ongoing in the Grand Canyon is probably inadequate to thoroughly understand all of the functions of the Canyon ecosystem. The program continues to develop and become more integrated and sophisticated. There is increasing recognition that a longer term research program is essential to develop the data that will allow an adequate understanding of resource responses identified by a monitoring program. It is also recognized that the monitoring program should be started during the present short-term studies and that it should be a complex, data rich program that will continue for years (a decade or more) after the completion of the EIS, in order to evaluate the consequences of the selected EIS alternative for dam and Canyon management.

The Grand Canyon ecosystem is an unique resource that we should make every effort to understand and protect.

REFERENCES

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U.S. Department of Interior. 1988b. Glen Canyon Environmental Studies, Executive Summaries of Technical Reports. Bureau of Reclamation, Flagstaff, Ariz.

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Closing Remarks

LUNA B. LEOPOLD, *University of California Berkeley, California*

When Glen Canyon was built on the Colorado River, there was one purpose in mind: to protect the water needs of the upper basin states that were going to be developed more slowly than California and the lower states. Glen Canyon was built in order to satisfy the division of water. The upper states have not finished taking their full consumptive use from the Colorado River. They still have numerous water needs, and therefore, the changes that we have seen in the past several decades will continue. The system is still changing and there is convincing evidence that it is out of equilibrium, as indicated by the sand bars, the vegetation, the water chemistry, the biota, and the water temperature. All of these parameters are changing at different rates. Some water entities have made their changes quickly, and others have not. But, since the upper states have not finished taking the water made available to them, we are going to see further impacts imposed upon the system—the timing of which we cannot forecast.

All of these changes are being superimposed on other unanticipated changes such as the possible climate change, the ordinary variability of runoff, and the changes that humans have brought about. We are dealing with something that is going to last a long time—much of which cannot be anticipated even if we keep studying it. The relationships between the physical, chemical, biological, economic, and other environmental processes and factors are complex. Considering these complexities, one cannot draw firm conclusions. After listening to the presentations at this symposium, I will make 10 closing remarks.

1. The deterioration of the totality of values will continue if no change is made in the operation of the Colorado River system. This progressive deterioration will not end.
2. The changing relationships among the physical, chemical, biological, and other environmental factors will possibly go unrecognized unless there is a comprehensive long-term observation program initiated as soon as possible. The changes could be greatly complicated if we introduce additional factors such as other exotic species or further planting of additional fish or other biota. Let us keep from complicating the system even more than it is.
3. The use of experimental flows to observe what happens under semicontrolled conditions is one of the scientific methods most likely to add new and useful information to our store of present knowledge. But the full use of these experiments will be greatly compromised if an adequate observation program is not in place at the time that they are operative. Experimental flows will, by the nature of the problem, be limited in scope and duration. We should not expect them to be more than a very modest beginning.
4. The Department of the Interior has failed to support a long term program of data collection. Such data collection is not costly compared with the cost of inadequate information. The cost of a stream gaging network, sediment, and water quality program is less than the cost of failure to have the proper information. Let me give a couple of examples. No adequate data were collected as to what was going to happen when the clear water was released downstream from Hoover Dam. The degradation below Hoover Dam was as much as 30 feet. The resulting degradation of the riverbed caused a flood problem in Yuma, and there has been a dredge operating in the Colorado River in the vicinity of Yuma since the dam was built. Now, of course, we make the best of a bad thing by making it into a federal wildlife refuge. In contrast, no one forecast what was going to happen below Fort Peck Dam. The river there did not have a degradation problem; it had an armoring problem. Thus, bank erosion of the Missouri River below Fort Peck had not been anticipated; no measurements were made, and it has been costly.
5. Political and economic forces drive the system—even at the expense of cost efficiency. Science cannot come to the support of management when curtailed by time limitations and lack of long-term support. Here is where the National Academy of Sciences (NAS) might come in. It is very difficult for individual agencies to bypass the Secretaries of their respective departments and go directly to Congress to have their say scientifically. The NAS can do so. The NAS has taken the wise step of trying to improve its endowment so it can initiate studies not financed by government agencies. I would suggest that the NAS do its part where the agencies cannot. The Academy should go directly to Congress.

6. The National Park Service has failed for years to do its part in exploring and explaning of its needs and purposes. When my brother wrote the Leopold Report for Secretary Udall, a main recommendation was that there must be a research organization in the National Park Service. It is not impossible to create a research organization. However, the National Park Service has made little attempt to do so.
7. The political forces that led to the preparation of an environmental impact statement at Glen Canyon Dam, I fear, are likely to use the environmental impact statement as the end product of their research program. They are likely as a result of it to eliminate the long-term monitoring and research program. They have made no promise to take this 5-year minimum program and support it. I greatly fear that we are likely to see the environmental impact statement used as a vehicle for simply saying that we've done our job and we've done the research—let's close it out. I hope that does not happen but we should keep our eyes open.
8. There are those of us who are meteorologists and who take seriously the possibility of climatic warming. The rivers in the western United States show that the climate changed in about 1945–1950, long before the meteorological records showed it. The climate changed about that time toward the cooler and more erratic, more moist phase. Later as the meteorological records became more complete, we could see how rivers reacted. There is still a great possibility that the climatic warming that might occur will lead to longer droughts than we have already seen. I think that we have to face the question of what happens in the case of a long drought. Let us study to see what the alternatives are and what kinds of results might occur.
9. It is discouraging to see that federal agency managers presently think that science has not contributed enough to give them an insight into how they might guide changes in dam operational procedures. The interpretation of scientific understanding, however limited or conditional, must be translated by the scientists into concrete recommendations designed for the manager. Perhaps we the scientists are not fulfilling our role. Science cannot be usefully applied unless there is built-in acceptance of the concept of incremental change. If we are going to make the change, for example, in the operation of a dam, it seems only logical to try it in small steps and see what happens. This has to be done with the understanding that we are going to make the change, see what happened, and then determine what should be done next. We cannot lay out long-term procedures that are likely to hold up forever. We must make small changes initially. But it should be understood very clearly by the people who are supporting the investigation that more changes will be needed.
10. The need for a long-term, uninterrupted program of observation and measurement is the unassailable conclusion of the studies made to date. On this point, neither managers nor any administrator can doubt the scientific

adequacy of the information supporting this result. The data-collection program should be designed with great care, it should consider a wide variety of data needs, and each part should be installed and operated as soon as practicable even though not all parts cannot necessarily begin at one time.

APPENDIXES

Appendix A

Symposium Program

Thursday, May 24	
8:00–8:30 a.m.	Zia Chamber • Registration • Continental Breakfast
8:30–9:00 a.m.	Welcome The Role of Science in Natural Resource Management: The Case for the Colorado River, *G. Richard Marzolf*
9:00–9:15 a.m.	Question/Answer Session
10:00–10:30 a.m.	Colorado River Basin Sediment, *Edmund Andrews*
10:30–10:45 a.m.	Question/Answer Session
10:45–11:30 a.m.	Panel Discussion: *G. Richard Marzolf* (moderator), *Julie Graf, William Graf, Marshall Moss, Peter Rowlands*
11:30 a.m.–12:45 p.m.	LUNCH-Anasazi South
12:45–1:15 p.m.	Lake Powell and Colorado River Water Chemistry, *Jack Stanford and James Ward*
1:15–1:30 p.m.	Question/Answer Session
1:30–2:00 p.m.	Algal and Invertebrate Biota in the Colorado River, *Dean Blinn and Gerald Cole*
2:00–2:15 p.m.	Question/Answer Session

2:15–2:45 p.m.	Native Fishes of the Grand Canyon: An Obituary?, *Wendell Minckley*
2:45–3:00 p.m.	Question/Answer
3:00–3:15 p.m.	BREAK
3:15–3:45 p.m.	Historic Changes in Vegetation Along the Colorado River in the Grand Canyon, *R. Roy Johnson*
3:45–4:00 p.m.	Question/Answer Session
4:00–4:45 p.m.	Panel Discussion: Duncan Patten (moderator), *Dennis Kubly, Larry Stevens, Robert Averett, William Lewis, Jr., David Policansky*
4:45 p.m.	ADJOURN
5:30–6:30 p.m.	RECEPTION-Eldorado Hotel, Courtyard
Friday, May 25	
8:00–8:30 a.m.	Zia Chamber • Continental Breakfast
8:30–9:00 a.m.	Operation of Glen Canyon Dam: Economics and Hydropower, *Michael Hanemann and Trevor Hughes*
9:00–9:15 a.m.	Question/Answer Session
9:15–9:45 a.m.	The Law and Politics of the Operation of Glen Canyon Dam, *Helen Ingram and A. Dan Tarlock*
9:45–10:00 a.m.	Question/Answer Session
10:00–10:30 a.m.	The Glen Canyon Environmental Studies Program Objectives, *David Wegner*
10:30–10:45 a.m.	Question/Answer Session
10:45–11:30 a.m.	Panel Discussion: *David Wegner (moderator); Richard Bishop, Clifford Barrett, Gary Weatherford, Herbert Fullerton, Trevor Hughes, Owen Williams*
11:30 a.m.–Noon	Glen Canyon Environmental Studies Integrated Research Plan, *Duncan Patten*
Noon–12:15 p.m.	Question/Answer Session
12:15–1:30 p.m.	*LUNCH*-Anasazi South
1:30–2:15 p.m.	Panel Discussion: *William Graf* (moderator), *Patricia Port, Jacqueline Wyland, A. Dan Tarlock, Wayne Deason*
2:15–3:00 p.m.	Concluding Remarks, *Luna B. Leopold*
3:00–3:15 p.m.	Question/Answer Session
3:15–3:30 p.m.	Closing, *G. Richard Marzolf*
3:30 p.m.	ADJOURN

APPENDIX B

Biographical Sketches of Committee Members

G. RICHARD MARZOLF (**Chairman**) received his Ph.D. from the University of Michigan in zoology. Dr. Marzolf has held various positions at Kansas State University, including assistant professor of zoology, associate professor of biology, and associate director of the division of biology. He is currently professor of biology. He was also visiting professor of zoology at the universities of Wisconsin, Oklahoma, and Oregon. He is a member of the International Association of Theoretical and Applied Limnology, American Society of Limnology and Oceanography, and Ecological Society of America. His areas of research are reservoir limnology and riparian/stream linkages. Dr. Marzolf is a former member of the NRC's Water Science and Technology Board and was chairman of the NRC's Glen Canyon Environmental Studies Committee from 1986 to 1990.

DAVID DAWDY received his M.S. in statistics from Stanford University. His professional experience is with the U.S. Geological Survey from 1951 to 1976 as research hydraulic engineer; adjunct professor of civil engineering from 1969 to 1972 at Colorado State University, Fort Collins; and assistant district chief for programming, California District, Water Resources Division from 1972 to 1975. He has served on numerous advisory groups, including NRC committees. From 1976 to 1980 he was chief hydrologist with Dames and Moore in Washington, D.C., and is currently a private consultant in surface water hydrology.

WILLIAM GRAF received his Ph.D. in August 1974 from the University of Wisconsin at Madison with a major in physical geography and a minor in water resources management. He specialized in fluvial geomorphology, hydrology, conservation policy and public land management, and aerial photographic interpretation. He was director, Center for Southwest Studies at Arizona State University, from 1981 to 1983. He has served as consulting geomorphologist for the U.S. Army Corps of Engineers in a research and advisory role concerning the environmental impact assessment of flood control works, Salt and Gila Rivers in Arizona; and for Camp, Dresser, and McKee, Inc., by writing a report on geomorphology and geology of the western Salt River Valley, Arizona. His research activities have included fluvial geomorphology and the effects of human activities on streams; public land management, especially wilderness preservation, and rapids in canyon rivers; and dynamics and recreation management, Arizona, Utah, and Colorado. Dr. Graf has published many articles and book chapters on the impact of suburbanization on fluvial geomorphology; resources, the environment, and the American experience; and the effect of dam closure on downstream rapids.

W. MICHAEL HANEMANN received his Ph.D. in public finance and decision theory from Harvard University in 1978. Since 1984 he has been associate professor in the Department of Agricultural and Resource Economics at the University of California at Berkeley. He has been a lecturer at the Department of Economics at Northeastern University, Boston; consultant, National Bureau of Economic Research, Inc., for the National Commission on Water Quality; economic consultant, Urban Systems Research and Engineering Inc.; and staff economist at Urban Systems and Engineering, Inc. Dr. Hanemann has also served as a consultant to the U.S. Environmental Protection Agency, U.S. Department of Energy, and California Department of Water Resources. He has been author and coauthor of many publications, such as "Theoretical and Empirical Study of the Recreation Benefits from Improving Water Quality in the Boston Area"; The Economics of Water Development and Use in California Water Planning and Policy: Selected Issues; and "Welfare Evaluations in Contingent Valuation Experiments with Discrete Responses" in the *American Journal of Agricultural Economics*, among others.

TREVOR C. HUGHES received his Ph.D. in civil engineering from Utah State University. His professional experience includes teaching since 1972 at Utah State University in the Civil and Environmental Engineering Department; research experience as NDEA fellow at Utah State; associate professor of Civil and Environmental Engineering, Utah Water Research Laboratory; and research scientist at International Institute of Applied Systems Analysis, Austria. Since 1971 he has conducted research projects on the management of salinity in the Colorado Basin, drought management analysis and policy design, regional planning of rural water supply systems, economic analysis of alternative water conservation concepts, river system operational models-Sevier River, and application and development of water demand functions for domestic water systems at recreation developments.

WILLIAM M. LEWIS, JR., received his Ph.D. from Indiana University in 1973 with emphasis on limnology. In 1974 he moved to the University of Colorado at Boulder as assistant professor of biology. At the University of Colorado he was assistant professor from 1974 to 1978, associate professor from 1978 to 1982, and professor after 1982. He is presently director of the University of Colorado Center for Limnology. Dr. Lewis was a Guggenheim fellow in 1980 to 1981 and has served on various NRC committees. His interests include aquatic food chains, trophic status of lakes, chemistry of surface water, mass transport by large rivers, and interactions between floodplains and rivers.

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, summers of 1977 to 1979; and consultant. He taught at Indiana University, Bloomington, from 1968 to 1981 and has also taught at the universities of Chicago, Michigan, Texas, and Utah. Since 1981 he has been the codirector of the Program in Energy and Environmental Law and professor of law of the TIT Chicago-Kent College of Law. In 1985 Mr. Tarlock was the Raymond F. Rice Distinguished Visiting Professor at the University of Kansas. He coauthored basic casebooks in environmental, land use, and water law. Mr. Tarlock served as a member of an NRC Committee on Pest Management and coauthored one of the basic casebooks in water law. He is a member of the Water Science and Technology Board and chairman of the WSTB Committee on Western Water Management.

APPENDIX C

Symposium Invitees

STANLEY ALBRIGHT, National Park Service
D. LARRY ANDERSON, Division of Water Resources, State of Utah
SUSAN ANDERSON, National Park Service
RICHARD ANGELOS, Colorado River Board of California
BRUCE BABBITT, Steptoe and Johnson, Phoenix, Arizona
VICTOR R. BAKER, University of Arizona
JAMES P. BARTLETT, Phoenix, Arizona
DINAH BEAR, Council on Environmental Quality
D. CRAIG BELL, Western States Water Council
JAMES BENNETT, U.S. Geological Survey
WILLIAM S. BIVINS, Federal Emergency Management Agency
BILL BRADLEY, Marlton, New Jersey
NANCY BRIAN, U.S. Bureau of Reclamation
ROBERT BROADBENT, McCarren International Airport, Nevada
NORMAN H. BROOKS, California Institute of Technology
RALPH BROOKS, Tennessee Valley Authority
QUINCALEE BROWN, Water Pollution Control Federation
EDWARD BRYAN, National Science Foundation
JACK BURKE, Department of the Interior
DURL BURKHAM, Carmichael, California
MICHAEL CAMPANA, University of New Mexico
STEVEN W. CAROTHERS, SWCA Environmental Consultants

JIM CARRIER, The Denver Post
GARY CARRUTHERS, Governor of New Mexico
DONALD L. CHERY, U.S. Nuclear Regulatory Commission
GEORGIE CLARK, Georgie's Royal River Rats, Nevada
PHILIP COHEN, U.S. Geological Survey
BONNIE COLBY, University of Arizona
JOHN CONOMOS, U.S. Geological Survey
DAVID CONRAD, Friends of the Earth
RICHARD A. CONWAY, Union Carbide Corporation
WAYNE COOK, U.S. Bureau of Reclamation
STEPHEN R. CORDLE, U.S. Environmental Protection Agency
JEAN CRANE, Wilderness River Adventures
KENNETH W. CUMMINS, University of Pittsburgh
COLBERT E. CUSHING, Batelle-Pacific Northwest
MALCOLM P. DALTON, Navajo Tribal Utility Authority
JACK DAVIS, Grand Canyon National Park
ROBERT DAY, Renewable Natural Resources Foundation
DONALD L. DE ANGELIS, Oak Ridge National Laboratory
JAMES DEACON, University of Nevada
JONATHAN P. DEANON, U.S. Department of the Interior
MICHAEL DELAND, Council on Environmental Quality
SENATOR DENNIS DE CONCINI, Washington, D.C.
PETER A. DICKSON, Harza Engineering Company
ROBERT DOLAN, University of Virginia
SENATOR PETE DOMENICI, Washington, D.C.
CHARLES DRAKE, Dartmouth College
CHARLES DUMARS, University of New Mexico
MARK DYKEMA, Trout Unlimited
JOHN ECHEVERRIA, American Rivers
LEO M. EISEL, Wright Water Engineers
ROBERT ELLIOT, Arizona Raft Adventures
ROBERT EULER, Preston, Arizona
DENNY FENN, National Park Service
RICK GOLD, U.S. Bureau of Reclamation
CHARLES R. GOLDMAN, University of California, Davis
THOMAS GRAF, Environmental Defense Fund
LLOYD GRIENER, Western Area Power Administration
EVE C. GRUNTFEST, University of Colorado
TERRY GUNN, Trophy Trout Tours, Arizona
EDWARD HALENBECK, U.S. Bureau of Reclamation
REED HARRIS, U.S. Bureau of Reclamation
TOM HARRIS, Sacramento Bee, California
JAMES P. HEANEY, University of Florida

RICHARD HEREFORD, U.S. Geological Survey
ROBERT HIRSCH, U.S. Geological Survey
RONALD HOFFER, U.S. Environmental Protection Agency
MARGE HOLLAND, Ecological Society of America
JACOB HOOGLAND, National Park Service
CHARLES C. HOWE, University of Colorado
EVELYN A. HOWELL, University of Wisconsin, Madison
CHARLES B. HUNT, Salt Lake City, Utah
WILLIAM JACKSON, National Park Service
MICHAEL C. KAVANAUGH, James M. Montgomery Consulting Engineers
SUSAN W. KIEFFER, Arizona State University
MICHAEL KRAUSS, U.S. Corps of Engineers
JOHN V. KRUTILLA, McLean, Virginia
HOWARD C. KUNREUTHER, University of Pennsylvania
BILL LEIBFRIED, Consultant, Flagstaff, Arizona
LUNA B. LEOPOLD, Emeritus, University of California, Berkeley
JOHN LESHY, Arizona State University
SIMON A. LEVIN, Cornell University
C. LAWRENCE LINSER, Department of Water Resources, Phoenix, Arizona
CHARLIE LISTON, U.S. Bureau of Reclamation
MARTIN LITTON, Menlo Park, California
IVO LUCCHITTA, U.S. Geological Survey
MANUAL LUJAN, Secretary, Department of the Interior
WALTER R. LYNN, Cornell University
HENRY MADDUX, Page, Arizona
WAYNE MARCHANT, U.S. Bureau of Reclamation
RICHARD MARKS, National Park Service
BILLY E. MARTIN, U.S. Bureau of Reclamation
TERRY MARTIN, Department of the Interior
KEN MAXEY, Western Area Power Administration
SENATOR JOHN McCAIN, Washington, D.C.
JEFF McCOY, Western Area Power Administration
J. WILLIAM McDONALD, Colorado Water Conservation Board
ROBERT R. MEGLEN, University of Colorado, Denver
LAREN MEYER, U.S. Forest Service
ANN MILES, Federal Energy Regulatory Commission
GEORGE MILLER, Pleasant Hill, California
LORAINE MINTZMYER, National Park Service
JERRY MITCHELL, Grand Canyon National Park
GOVERNOR ROSE MOFFORD, Phoenix, Arizona
NANCY Y. MOORE, The Rand Corporation

DICK MORGAN, U.S. Fish And Wildlife Service
ROBERT E. MURPHY, National Aeronautics and Space Administration
PHILIP MUTZ, New Mexico Interstate Stream Commission
EDGAR H. NELSON, U.S. Department of Agriculture
ALAN B. NICHOLS, Water Pollution Control Federation
ED NORTON, Grand Canyon Trust
DONALD O'CONNOR, Manhattan College
MIKE O'DONNELL, U.S. Bureau of Reclamation
BETTY H. OLSON, University of California, Irvine
W. KENT OLSON, American Rivers Conservation Council
DAVID O. ONSTAD, Arizona Power Authority
FRANK OSTERHOUDT, U.S. Department of the Interior
LARRY PAULSEN, University of Nevada
ERNIE PEMBERTON, Highland Ranch, Colorado
BILL PERSON, Arizona Game and Fish Department
RANDY PETERSON, U.S. Bureau of Reclamation
WILLIAM PLUMMER, Arizona Department of Water Resources
STANLEY PONCE, National Park Service
RICHARD PORTER, U.S. Bureau of Reclamation
MICHAEL PUCHERELLI, U.S. Bureau of Reclamation
TIM RANDLE, U.S. Bureau of Reclamation
SALLY RANNEY, American Wildlands
P. SURESH RAO, University of Florida
KEN REID, American Water Resources Association
WILLIAM RICHARDSON, Washington, D.C.
JOHN RIDENHOUR, Department of the Interior
MARC REISNER, San Francisco, California
PAUL G. RISSER, University of New Mexico
ROLAND ROBISON, U.S. Bureau of Reclamation
MIKE ROLUTI, U.S. Bureau of Reclamation
WILLIAM ROPER, U.S. Army, Corps of Engineers
PATRICIA ROSENFIELD, The Carnegie Corporation of New York
DAVID RUBIN, U.S. Geological Survey
JIM RUCH, Grand Canyon Trust
DONALD D. RUNNELLS, University of Colorado
JOHN SCHAAKE, National Weather Service
JACK SCHMIDT, Middlebury College
LARRY J. SCHMIDT, U.S. Department of Agriculture
JAMES R. SEDELL, Forestry Sciences Lab, Corvallis, Oregon
HAROLD SERSLAND, U.S. Bureau of Reclamation
GENE SHOEMAKER, U.S. Geological Survey
DUANE SHROUFE, Arizona Game and Fish Department
ROBERT SIEVERS, University of Colorado

TOM SLATER, U.S. Bureau of Reclamation

JIM DUNGAN SMITH, U.S. Geological Survey

SOROOSH SOROOSHIAN, University of Arizona

MICHAEL SPEAR, U.S. Fish and Wildlife Service

JACK L. STONEHOCKER, Colorado River Commission of Nevada

ROYAL SUTKES, Tulane University

MARC SYLVESTER, U.S. Geological Survey

HOWARD TAYLOR, U.S. Geological Survey

FRANK THOMAS, Federal Emergency Management Agency

HUGO THOMAS, Department of Environmental Protection, Connecticut

JOHN TURNER, Department of the Interior

RAYMOND M. TURNER, U.S. Geological Survey

MORRIS K. UDALL, Washington, D.C.

HOWIE USHER, Cottonwood, Arizona

CHARLES VAN RIPER, National Park Service

JIM DE VOS, JR., Arizona Game and Fish Department

ANDREW WALCH, U.S. Department of Justice

JAMES R. WALLIS, IBM Watson Research Center

PETER WARREN, The Arizona Nature Conservancy

ROBERT WEBB, U.S. Geological Survey

MICHAEL WELSH, HBRS Consulting, Wisconsin

DICK WHITE, U.S. Bureau of Reclamation

MARK WIERINGA, Western Area Power Administration

ROBERT WILLIAMS, U.S. Bureau of Reclamation

SUSAN WILLIAMS, Gover, Stetson, Williams and West, Albuquerque, New Mexico

RICHARD WILSON, U.S. Geological Survey

SENATOR TIMOTHY WIRTH, Washington, D.C.

FRANK J. WOBBER, U.S. Department of Energy

M. GORDON WOLMAN, The Johns Hopkins University

CHUCK WOOD, Glen Canyon National Recreation Area

MIKE YARD, U.S. Bureau of Reclamation

JIM YOUNG, U.S. Fish and Wildlife Service

ARTHUR ZEIZEL, Federal Emergency Management Agency

GERALD R. ZIMMERMAN, Upper Colorado River Commission

Representatives of the following organizations were invited to attend:

COLORADO RIVER FISHES RECOVERY TEAM, U.S. Fish and Wildlife Service

SUPERINTENDENT, Lake Mead National Recreational Area

NEW MEXICO GAME AND FISH DEPARTMENT, Santa Fe, New Mexico

NAVAJO FISH AND WILDLIFE, Window Rock, Arizona

HAVASUPAI TRIBE, Supai, Arizona

HOPI TRIBE, Kykotsmovi, Arizona

NAVAJO TRIBE, Window Rock, Arizona

KAIBAB-PAIUTE TRIBE, Fredonia, Arizona

ARIZONA NATURE CONSERVANCY, Tucson, Arizona

ARIZONA WILDERNESS COALITION, Phoenix, Arizona

DESERT FISHES COUNCIL, Bishop, California

FRIENDS OF THE RIVER, Sacramento, California

HIGH COUNTRY NEWS, Paonia, Colorado

NATURAL PARKS AND CONSERVATION ASSOCIATION, Cottonwood, Arizona

SIERRA CLUB GRAND CANYON CHAPTER, Phoenix, Arizona

SIERRA CLUB, San Francisco, California

WESTERN RIVER GUIDES ASSOCIATION, Denver, Colorado

GRAND CANYON RIVER GUIDES, Flagstaff, Arizona

THE WILDERNESS SOCIETY, Phoenix, Arizona

THE CONSERVATION FOUNDATION, Washington, D.C.

NATURAL RESOURCES DEFENSE COUNCIL, San Francisco, California

APPENDIX D

Glen Canyon Environmental Studies Technical Reports and Related Documents

A list of the Glen Canyon Environmental Studies (GCES) technical reports is provided below. The reports are organized with the final report listed first, followed by technical report titles and authors for Sediment and Hydrology (numbers 2–11), Aquatic Biology (numbers 12–17), Terrestrial Biology (numbers 18–26), Recreation (numbers 27–31), and Dam Operations (numbers 32–33). Other reports relating to the GCES Phase I program are also listed (numbers 34–39).

National Technical Information Service (NTIS) accession numbers are listed for each report. These reports are available from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161
Phone: (703) 487-4650

Three reports (2, 3, and 5) are also available from:

U.S. Geological Survey
Books and Open-File Reports Section
Federal Center, Building 810
Denver, Colorado 80225

1. Glen Canyon Environmental Studies final report. (U.S. Department of the Interior) [NTIS No. PB88-183348/AS]
2. Debris flows from tributaries of the Colorado River, Grand Canyon National Park, Arizona. (R. H. Webb, P. T. Pringle, and G. R. Rink; USGS Open-File Report 87-118, pending publication as a USGS Professional Paper) [NTIS No. PB88-183355/AS]
3. The rapids and waves of the Colorado River, Grand Canyon, Arizona. (S. W. Kieffer, USGS Open-File Report 87-096, pending publication as a USGS Professional Paper) [NTIS No. PB88-183363/AS]
4. Sonal Patterns of the Colorado River bed in the Grand Canyon. (R. P. Wilson) [NTIS No. PB88-183371/AS]
5. Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona. (J. C. Schmidt and J. B. Graf, USGS Open-File Report 87-555, pending publication as a USGS Professional Paper) [NTIS No. PB88-183389/AS]
6. Sandy beach area survey along the Colorado River in the Grand Canyon National Park. (R. Ferrari) [NTIS No. PB88-183389/AS]
7. Trends in selected hydraulic variables for the Colorado River at Lee's Ferry and near Grand Canyon for the period 1922-1984. (D. E. Burkham) [NTIS No. PB88-216098/AS]
8. Sediment data collection and analysis for five stations on the Colorado River from Lee's Ferry to Diamond Creek. (E. L. Pemberton) [NTIS No. PB88-183397/AS]
9. Unsteady flow modeling of the releases from Glen Canyon Dam at selected locations in Grand Canyon. (J. Lazenby) [NTIS No. PB88-1833405/AS]
10. Sediment transport and river simulation model. (C. J. Orvis and T. J. Randle) [NTIS No. PB88-183413/AS]
11. Results and analysis of STARS modeling efforts of the Colorado River in Grand Canyon. (T. J. Randle and E. L. Pemberton) [NTIS No. PB88-183413/AS]
12. Effects of varied flow regimes on aquatic resources of Glen and Grand Canyons. (H. R. Maddux, D. M. Kubly, J. C. deVos, Jr., W. R. Persons, R. Staedicke, and R. L. Wright) [NTIS No. PB88-183439/AS]
13. Colorado River water temperature modeling below Glen Canyon Dam. (R. Ferrari) [NTIS No. PB88-183447/AS]
14. Instream flow microhabitat analysis of the Glen Canyon Dam tailwater. (D. L. Wegner) [NTIS No. PB89-180236, GCES/14/87]
15. The effects of steady versus fluctuating flows on aquatic macroinvertebrates in the Colorado River below Glen Canyon Dam, Arizona. (W. C. Leibfried and D. W. Blinn) [NTIS No. PB88-206362/AS]
16. *Cladophora glomerata* and its diatom epiphytes in the Colorado River through Glen and Grand Canyons: distribution and desiccation tolerance.

(H. D. Usher, D. W. Blinn, G. G. Hardwick, and W. C. Leibfried) [NTIS No. PB88-183454/AS]

17. Zooplankton of the Colorado River: Glen Canyon Dam to Diamond Creek. (L. R. Haury) [NTIS No. PB88-183462/AS]
18. Evaluation of riparian vegetation trends in the Grand Canyon using multitemporal remote sensing techniques. (M. J. Pucherelli) [NTIS No. PB88-183470/AS]
19. Effects of post-dam flooding on riparian substrate, vegetation, and invertebrate populations in the Colorado River corridor in Grand Canyon, Arizona. (L. E. Stevens and G. L. Waring) [NTIS No. PB88-183488/AS]
20. Aerial photography comparison of the 1983 high flow impacts to vegetation at eight Colorado River beaches. (N. J. Brian) [NTIS No. PB89-180244]
21. The effects of recent flooding on riparian plant establishment in Grand Canyon. (G. L. Waring and L. E. Stevens) [NTIS No. PB88-183496/AS]
22. Effects of post-Glen Canyon Dam flow regime on the old high water line plant community along the Colorado River in Grand Canyon. (L. E. Anderson and G. A. Ruffner) [NTIS No. PB88-183512/AS]
23. Fluctuating flows from Glen Canyon Dam and their effect on breeding birds of the Colorado River. (B. T. Brown and R. R. Johnson) [NTIS No. PB88-183512/AS]
24. Monitoring bird population densities along the Colorado River in Grand Canyon. (B. T. Brown) [NTIS No. PB88-183520/AS]
25. Monitoring bird population densities along the Colorado River in the Grand Canyon: 1987 breeding season. (B. T. Brown) [NTIS No. PB88-103311/AS]
26. Lizards along the Colorado River in Grand Canyon National Park: possible effects of fluctuating river flows. (P. L. Warren and C. R. Schwalbe) [NTIS No. PB88-183538/AS]
27. Glen Canyon Dam releases and downstream recreation: an analysis of user preferences and economic values. (R. C. Bishop, K. J. Boyle, M. P. Welsh, R. M. Baumgartner, and P. R. Rathbun) [NTIS No. PB88-183546/AS]
28. The effect of flows in the Colorado River on reported and observed boating accidents in Grand Canyon. (C. A. Brown and M. G. Hahn) [NTIS No. PB88-183553/AS]
29. Boating accidents at Lee's Ferry: a boater survey and analysis of accident reports. (L. Belli and R. Pilk) [NTIS No. PB88-183561/AS]
30. Simulating the effects of dam releases on Grand Canyon river trips. (A. H. Underhill and R. E. Borkan) [NTIS No. PB880183579/AS]
31. An analysis of recorded Colorado River Boating accidents in Glen

Canyon for 1980, 1982, and 1984, and in Grand Canyon for 1981 through 1983. (A. H. Underhill, M. H. Hoffman, and R. E. Borkan) [NTIS No. PB88-143515/AS]

32. Colorado River Storage Project constraints and operation of Glen Canyon Dam. (D. L. Wegner) [NTIS No. PB89-143515/AS]
33. Colorado River law. (D. L. Wegner) [NTIS No. PB89-143523/AS]
34. River and dam management: a review of the Bureau of Reclamation's Glen Canyon Environmental Studies. (Committee to Review the Glen Canyon Environmental Studies, Water Science and Technology Board, National Research Council, National Academy Press, Washington, D.C., 1987, 203 pp.) [NTIS No. PB88-177175/AS]
35. Executive review committee final report. (U.S. Department of the Interior, Fish and Wildlife Service, National Park Service, Bureau of Reclamation, Western Area Power Administration) [NTIS No. PB89-11962/AS]
36. Executive summaries of technical reports. (U.S. Department of the Interior) [NTIS No. pending]
37. Submerged cultural resources site report: Charles H. Spencer mining operation and paddle wheel steamboat. Glen Canyon National Recreation Area. (Toni Carrell (ed.), Submerged Cultural Resources Unit, National Park Service, Southwest Cultural Resources Center Profession Papers, Number 13, Santa Fe, New Mexico, 1987, 166 pp.) [Published by U.S. Government Printing Office: 1987-573-737 Region No. 8, NTIS No. pending]
38. Glen Canyon Environmental Studies Phase II and III plan for implementation. (Bureau of Reclamation) [NTIS No. PB89-180228]
39. Glen Canyon Environmental Studies Phase II technical study plan outline: fiscal year 1989 and process for completion of the technical studies. (Bureau of Reclamation) [NTIS No. pending]

Additional GCES Publications

1. Executive Summaries of Technical Reports, Glen Canyon Environmental Studies, Phase I. Bureau of Reclamation. October 1989.
2. Glen Canyon Environmental Studies, Five Thousand Cubic Feet per Second Flow Study. Bureau of Reclamation. March 1990.
3. Aggradation and Degradation of Alluvial Sand Deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona. U.S. Geological Survey. [NTIS No. PB90-244914LEU]
4. Changes in Winter Distribution of Bald Eagles Along the Colorado River in Grand Canyon National Park. Bryan T. Brown, Robert Mesta, Lawrence Stevens, and John Weisheit. Journal of Raptor Research 23 (3):110–113.
5. The Effects of Fluctuating Flows from Glen Canyon Dam on Bald Eagles

and Rainbow Trout at Nankoweap Creek Along the Colorado River, Arizona. Bryan T. Brown and William C. Liebfried. October 1990.

6. Glen Canyon Environmental Studies, Draft Integrated Research Plan. Bureau of Reclamation. August 1990.
7. Evaluation of Methods to Estimate Power System Impacts of Potential Changes in Glen Canyon Powerplant Operations. Bureau of Reclamation. April 1990.