GLEN CANYON ENVIRONMENTAL STUDIES FINAL REPORT

JANUARY 1988

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ACKNOWLEDGMENTS

The development of the Glen Canyon Environmental Studies (GCES) has been a team effort that has required the coordination of many individuals, agencies, and groups. The final report is a result of a continual consolidation of data, analyses, and results.

The strength of the GCES has always been with the researchers and scientists. This dedicated group of people has displayed abilities and desire far beyond that normally associated with studies of this magnitude. They are to be commended for their professionalism, attention to details, desire to work under trying conditions, and their feelings for the resources that we studied. These attributes are not something that were gained from a textbook or an agency manual; they came from the heart.

The coordination of the individual studies and the tying together of the reports could not have been accomplished without the help of the three subteam leaders: Reed Harris, Biology; Mike O'Donnell, Recreation; and Jerold Lazenby, Sediment and Hydrology.

The development of the first level of subteam reports was primarily accomplished through the Report Preparation and Integration Group. In addition to the subteam leaders, the following people were unstoppable: Susan Anderson, Bryan Brown, Henry Maddux, Julie Graf, Jack Schmidt, Ernie Pemberton, Rich Bishop, Curt Brown, and Martha Hahn. This group provided the initial integration of the reports and the persistence necessary to identify the relationships and impacts. As the operations information was integrated into the effort, Randy Peterson proved to be a valuable asset to the team.

The final report that is presented here was developed primarily by the Technical Writing Integration Group. These individuals were the ones who spent the time and energy necessary to consolidate the results into a sound and coherent package. Curt Brown provided the unflinching drive behind this group, with excellent support from Susan Anderson, Julie Graf, and Reed Harris. As always, this was a group effort with continual feedback from the other team members. The technical editing of the report was accomplished by Dorothy House, Ron Borkan, and Steve Carothers. Graphics were done by Dolber B. Spalding and Lauren Lucas.

Over the course of the GCES, additional people have provided the bureaucratic support and guidance necessary to accomplish our goals. Cliff Barrett, BOR's Upper Colorado Regional Director; Wayne Cook (BOR); Harold Sersland (BOR); Bill Rinne (BOR); Richard Marks, Grand Canyon Superintendent (NPS); John Thomas (former NPS); Martha Hahn (NPS); Steve Hodapp (NPS); Jim deVos (AGF); Bob MacNish (USGS); and Frank Baucom (FWS). Tom Gamble (BOR) and Dick White (BOR) of Glen Canyon Dam provided flow information, help, and support, often when it was the unpopular thing to do. Thank you.

Intellectual, moral, and logistical support for the project and the continual push for excellence came from a wide variety of sources. Intellectual stimulation, striving for excellence, and belief in the effort came from Susan Kieffer, Steve Carothers, and Patricia Port. Sue provided the GCES a home when we needed one and was continually there to offer input on how to deal with the scientific and interpretation problems. Steve provided us with the historical perspective and importance of what we were striving toward. Dealing with the multiple Interior agencies involved in the GCES has definitely been a "learning" experience, an experience more often dealing with frustration than action. Patricia Port (USDI) has played a very significant role in helping unravel the logic behind agency positions and has always had a helpful suggestion or word of encouragement when needed. Thanks. Logisitical support during the course of the GCES was coordinated through many of the concessionaires in the river community, but was the primary responsibility of Humphrey Summit Associates, Arizona River Runners, and Sleight Expeditions. An assortment of professional boatmen provided the support and field help necessary to accomplish the data collection effort. No amount of thanks can cover the hours and effort that they provided to the Studies.

Nancy Brian and Lauren Lucas need to be recognized for their ability to cope with a variety of bureaucratic, technical, and logistical problems. As the only true staff of the GCES, these two people have excelled and shown abilities to coordinate and withstand the pressures of the GCES program and, far worse, the demands of a cramped office and a workaholic supervisor. Thanks.

This list is but a few of the many people who have been involved in the GCES program. Additional people have spent long and hard hours in the field and in the labs. I regret that time and space do not allow a thank you to each. They are all special. Above all the rhetoric that often goes with an effort of this magnitude, this group of people has shown the ability to withstand a great many hardships and still retain their desire and drive. They have been able to keep in perspective the fact that we were working for the betterment of the resources of the Grand Canyon. True, the Grand Canyon was here long before any of us and quite likely will be here long after we have departed. However, the people of the GCES had one common tie among us all, and that was that we believed in what we were doing and in the fact that it is our responsibility to minimize our impacts on the resources. We are the stewards of the land. That responsibility cannot be delegated or transferred. It has been my privilege to have worked with all of them. They truly are the heart and soul of the GCES. A tip of the oar to all.

Dave Wegner
GCES Study Manager
July 1987

SUMMARY AND PRINCIPAL CONCLUSIONS

Inter-Agency Study Assessed Impacts Of Glen Canyon Dam Operations

This report presents the findings of the Glen Canyon Environmental Studies (GCES). In December of 1982, the Secretary of the Interior directed the Bureau of Reclamation (BOR) to initiate a multi-agency study to address the concerns of the public and other federal and state agencies about possible negative effects of the operations of Glen Canyon Dam on downstream environmental and recreational resources. <u>This study was not intended nor designed to lead directly to changes in dam operations.</u> Any decision to make operational changes would require feasibility studies and National Environmental Policy Act (NEPA) compliance activities to assess the impact of those changes on the primary mandate of the Colorado River Storage Project (water storage and delivery), power generation, and economic considerations, as well as on the environment and recreation.

The GCES study goals were, first, to investigate the impact of several aspects of current dam operations on the existing environmental and recreational resources in the Glen Canyon National Recreation Area and Grand Canyon National Park--specifically the effect of very high, very low, and strongly fluctuating releases from the dam. Second, if adverse impacts to downstream resources were found, the study was to determine whether modifications made to dam operations, within the constraints of Colorado River Storage Project water delivery requirements, could reduce those impacts. These modifications were to be based on environmental needs and did not include a full economic, cost-benefit analysis. To accomplish the study goals, over 30 technical studies in the fields of biology, recreation, and sediment and hydrology were conducted by over 100 researchers.

The GCES Determined That Some Aspects Of The Operation Of Glen Canyon Dam Have Substantial Adverse Effects On Downstream Environmental And Recreational Resources

Construction of the dam and subsequent regulation of river flows have changed downstream resources in many ways. Some of these changes, such as the increase in riparian vegetation, the development of an exceptional trout fishery, and the extended white-water boating season are beneficial. However, two aspects of current operations, flood releases and fluctuating releases, were found to have substantial adverse effects on downstream resources. Impacts were assessed by comparing current operations, which include floods and fluctuations, to operations which would avoid flood releases and which would convert fluctuating releases to steady releases.

Flood Releases Cause Damage To Beaches And Terrestrial Resources

A flood release is defined in this report as a discharge greater than the maximum powerplant release. During the course of the GCES, maximum powerplant releases were 31,500 cubic feet per second (cfs). During flood releases, substantial quantities of riparian vegetation are scoured away, drowned, or buried by redeposited sand. As a result of the flood releases of 1983, vegetation loss in some areas reached 50 percent, and 95 percent of the marshes and 75 percent of the nests of some riparian bird species were destroyed.

Because the dam cuts off the main pre-dam source of sediment to the river downstream, flood releases of sediment-free water cause significant and irreversible degradation of the environment by eroding a substantial portion of the sand deposits. These deposits provide substrate for riparian vegetation and wildlife habitat and are highly valued as campsites by boaters. Significant loss of sand beaches would reduce by approximately 50 percent the recreation benefits (not commercial revenues) associated with white-water boating.

Under Current Operations, Flood Releases Will Occur In About One Of Every Four Years

Flood releases occur about one in four years due to reservoir storage targets and errors in forecasted runoff (among other variables). Current data are sufficient to show that this frequency of flooding would be damaging to downstream resources, but are insufficient to determine precisely the frequency of flooding that resources can tolerate in the long-term. Based on observations of the natural system in Grand Canyon, flood releases should be avoided until a tolerable frequency can be better defined. Current knowledge indicates that even a frequency as low as one flood in twenty years will produce a net long-term loss of camping beaches and substrate, although at a rate reduced from that caused by current operations.

Two methods of frequency analysis were used to arrive at the one-in-four-year flood frequency. Operating procedures and methods in place during the GCES study period were used in calculating the frequency of spills.

Fluctuating Releases Primarily Affect Recreation and Aquatic Resources

Except during periods of very high runoff, the amount of water released from Glen Canyon Dam is varied on an hourly basis, often with two peaks and two troughs daily. This is done to provide electrical power when it is most needed during the day. These fluctuations can cause the river level to change by up to 13 feet. Fluctuating releases stay below 31,500 cfs and are therefore not as detrimental as floods for terrestrial resources. However, they have a deleterious effect on recreation and aquatic resources. The quality of fishing and white-water boating is reduced by approximately 15 percent under fluctuating releases as compared to steady releases.

Fluctuating releases have a greater impact on aquatic than on terrestrial resources. Fluctuations at any time of the year strand fish. Fluctuations during the summer months reduce habitat for larval native fishes. Fluctuations in the winter months reduce the natural reproduction of trout by exposing spawning beds and denying access of reproducing adults to tributaries. However, short periods of fluctuations at other times may increase food availability and trout growth.

Beaches deposited during high, steady flows are rapidly eroded when exposed to either fluctuating or steady lower flows, but the rate of erosion diminishes and equilibrium is reached after several years of similar releases. The stable beach area that develops in response to fluctuating flows is smaller than that developed during steady flows of the same annual volume, and could be substantially smaller depending upon release patterns.

Modified Operations Could Protect Or Enhance Most Resources

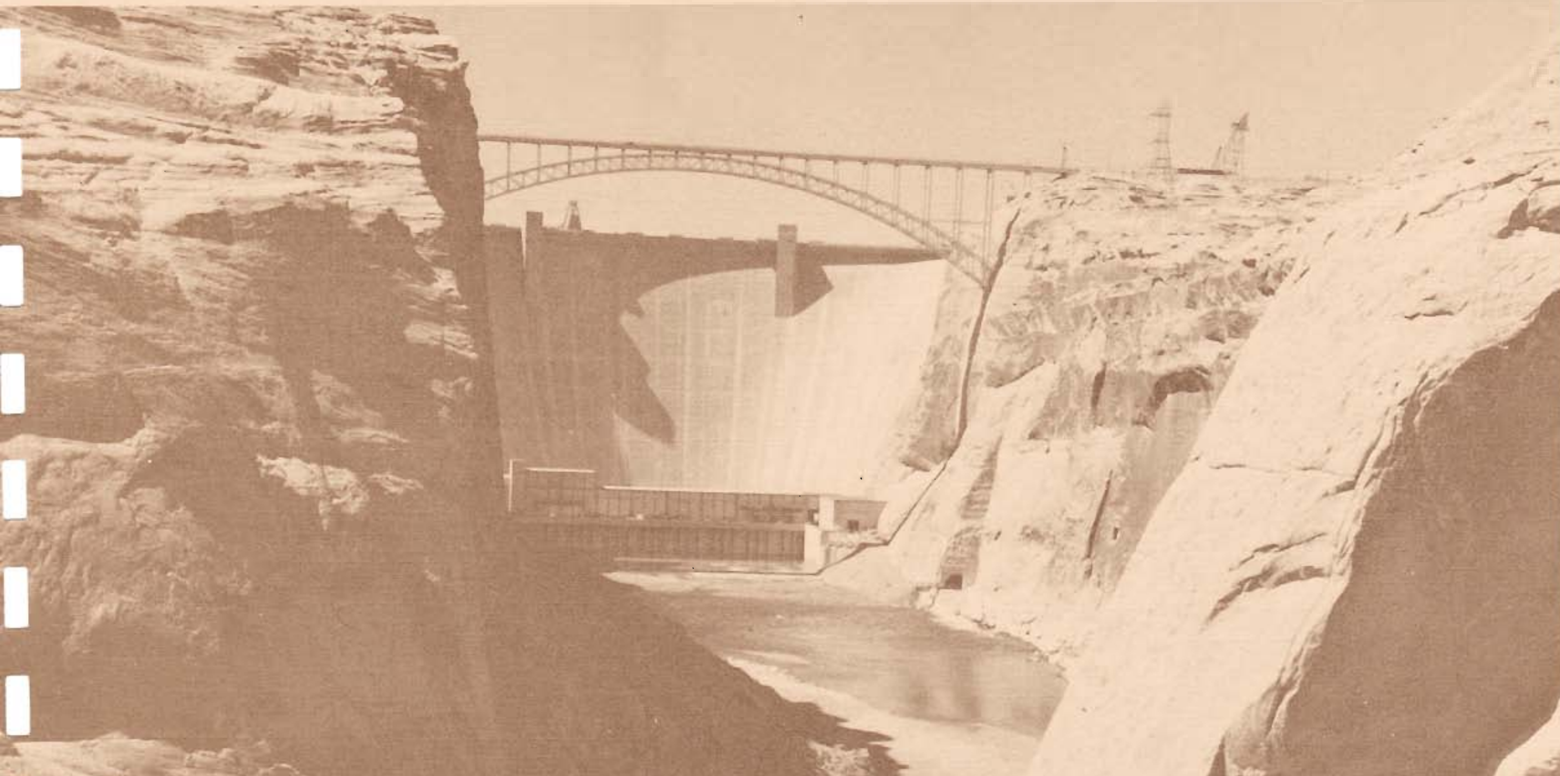
The GCES found that changes in operation of the dam to reduce fluctuations and avoid flood releases could reduce the resource losses occurring under current operations and, in some cases, even improve the status of the resources. Five modified patterns of operations were designed, each to address one or more critical resources. These patterns have been constrained only by the need to release a minimum of 8.23 million acre feet (maf) per year, maintain minimum flows of 1,000 cfs in winter and 3,000 cfs in summer, and stay within the designated powerplant capacity of 31,500 cfs. These modifications only approximate ideal release patterns for individual downstream resources. They illustrate the types of changes that would protect or enhance resources, but do not represent the full range of possible options. <u>These modifications should not be considered as fully developed or recommended operational schemes.</u>

Our Understanding of the Relationships Between Dam Operations And Downstream Resources Is Not Complete

The limited time available for the Glen Canyon Environmental Studies increases the uncertainty of long-term predictions made from data collected during the study. The coincidence of the GCES with high flows that were not typical of pre-1983 releases limited our ability to determine the response of resources to low and fluctuating flows. These high releases required major changes in research design as the studies were in progress. We believe, however, that the more general conclusions that dam operations affect downstream resources and that modified operations would better protect these resources, would not change due to these uncertainties.

Nowhere were time and flow limitations more strongly felt than in determining the effects of dam operations on the humpback chub. The legal and biological status of this species makes decisions based on inadequate or incomplete information particularly dangerous. In this respect, we have erred on the side of caution and wish to reemphasize the need for further studies with appropriate flow regimes to correctly assess the effects of dam operations on this endangered species.

FINAL REPORT



Glen Canyon Unit, Colorado River Storage Project, general view of Glen Canyon Dam and powerhouse from Pump Plant Road, downstream, by Stan Rasmussen, June 24, 1964. Photo courtesy of Bureau of Reclamation, Upper Colorado Region, (#P 557 400 252 NA). Mean daily release of 980 cubic feet per second.

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SECTION I: INTRODUCTION

The Glen Canyon Environmental Studies Assessed The Impact of Dam Operations

The Glen Canyon Environmental Studies (GCES) are a multi-agency effort to study the impacts of Glen Canyon Dam operations on the environmental and recreational resources of the Colorado River downstream of the dam. This reach of river flows first through 15 miles of Glen Canyon, then through 277 miles of the Grand Canyon before entering Lake Mead (see location maps in Figures I-1 and I-2).

In recognition of the concerns of the public and other governmental agencies, the Bureau of Reclamation (BOR) was directed by the Department of the Interior to conduct a general study of the short- and long-term effects of current Glen Canyon Dam operations on vegetation, wildlife, fisheries, recreation, beaches, and other environmental resources. These studies were to evaluate fluctuating flows, low flows, and high flows to determine their effect on resources. The GCES were a cooperative effort between the BOR, the National Park Service (NPS), and the U.S. Fish and Wildlife Service (FWS). Cooperation and contributions to the study came from the Arizona Department of Game and Fish (AGF), the U.S. Geological Survey (USGS), private consultants, universities, and private and commercial river runners and guides.

The studies were formulated by the Department of the Interior on December 8, 1982, to answer two questions:

(1) Are current operations of the dam, through control of the flows in the Colorado River, adversely affecting the existing river-related environmental and recreational resources of Glen Canyon and Grand Canyon?

(2) Are there ways to operate the dam, consistent with Colorado River Storage Project (CRSP) water delivery requirements, that would protect or enhance the environmental and recreational resources?

The modified dam operations developed and evaluated in answer to the second question were designed only with the goal of protecting or enhancing downstream environ-

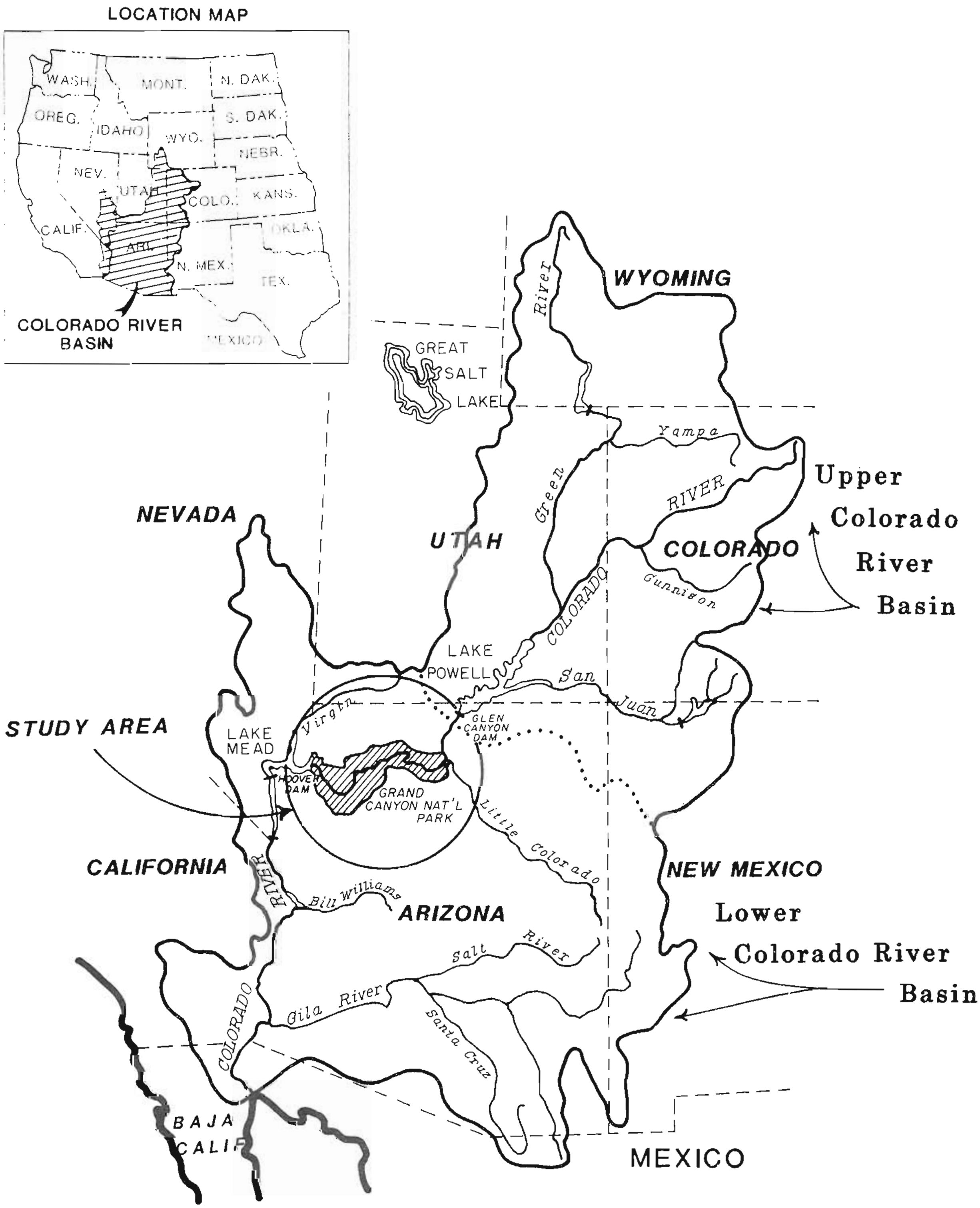

Figure I-1. The Colorado River watershed showing Upper and Lower Basins, drainages, dams, and impoundments.

mental and recreational resources, constrained by the operating objectives to deliver 8.23 million acre-feet (maf) of water annually, maintain minimum flows of 1,000 cfs in winter and 3,000 cfs in summer, and stay within the designated powerplant capacity of 31,500 cfs. These modified schemes are illustrations of flow patterns that could protect resources during the periods of the year when they are sensitive to flows. It should be recognized that changes to operations to protect or benefit downstream resources might have negative consequences for other CRSP functions. In evaluating possible modifications to operations, **these studies have assessed only benefits and costs to the environment and recreation.** Assessment of the implications for power generation, revenue, water delivery, or other system and legal requirements was not within the scope of the GCES. These studies, therefore, were not intended nor designed to lead directly to changes in dam operations but to provide the technical information necessary to enable decision makers to assess the significance of impacts.

OBJECTIVES of Dam

Studies Provide Basis For Secretarial Decision

This report has been reviewed for technical accuracy by the participating agencies. In addition, an Executive Review Committee composed of representatives from these agencies will determine the policy implications of the studies. The report is also being reviewed by a committee of the National Research Council of the National Academy of Sciences. The participating agencies on the Executive Review Committee and the National Academy of Sciences GCES Review Committee will separately make recommendations concerning the technical adequacy of the report and future courses of action that should be taken.

In addition, the Fish and Wildlife Service is reviewing the GCES data on the humpback chub to develop a new biological opinion for the protection or recovery of the species.

Although the range of decisions that might ultimately be made by the Secretary of the Interior in response to the GCES has not yet been determined, several outcomes are possible, including:

- Determination that the defined impacts are acceptable and that no change in the basic operating criteria is indicated.

- Determination that sufficient data is lacking to make an operational decision. The monitoring of specific resources and/or initiation of specific studies may be required.

- Recommendation to explore new operating criteria and order the National Environmental Policy Act (NEPA) process to begin. Through the NEPA process, all impacts, including physical, social, and economic would be evaluated for each operating alternative and full public involvement would be initiated.

Over Thirty Studies Are Integrated In This Final Report

This report is based upon the results of over 30 technical studies, background analyses, and associated literature reviews. Over 100 researchers from government agencies, universities, and private consulting firms participated in the four-year GCES effort.

Many kinds of data were collected and analyzed for the study. Hourly dam release records for 25 years were tabulated and analyzed. Aerial and ground photographs taken over a 30-year period were used in assessing temporal changes in river hydraulics, backwater availability, changes in camping beaches and sand volume, and broad scale changes in riparian vegetation.

ECOLOGY STUDIES

1) PLANTS

2) BIRDS

3) FISH

Three ecological studies, including monitoring of 14,000 individual plants and 900 seedlings, related river flows to seedling establishment, growth, and mortality in order to predict future changes in the vegetative community. Although other groups of vertebrates were studied, riparian birds were emphasized; approximately 30 species and over 500 nests were studied over six years.

Studies of the impact of dam releases on fish and the aquatic food base involved analyzing the chemical and physical properties of water, and collecting and examining over 30,000 fish to determine fish habitat preference, movement patterns, reproduction requirements, and food habits.

Surveys of 286 white-water guides, 1,038 white-water boaters, 446 Glen Canyon anglers, and 415 Glen Canyon day-rafters were conducted to assess the effect of dam releases on the quality of these recreational activities. To assess the impact of dam releases on Grand Canyon and Glen Canyon boating accidents, eight years of NPS accident records were studied and over 5,000 boats were observed running rapids under different flow conditions.

HUMAN SURVEYS
IMPACT ON THEIR RECREATION EMPLOYMENT

Factors affecting transport and storage of sediment in the river channel were assessed from discharge records from 1922 to 1984, as well as from 874 discharge measurements and 1,943 suspended sediment and 976 riverbed samples taken during the study. Thirty-six tributaries were examined to assess the contribution of sediment by small tributaries to the main channel. Sediment data from the three largest tributaries were used to estimate the amount of sand contributed by these major sources. The data from sediment sampling and surveys of river cross sections were used in the development of predictive models of sediment transport.

SEDIMENT TRANSPORT

TRIBUTARY CONTRIBUTION TO SEDIMENT

Changes in camping beaches and other sand deposits along the channel margins were measured at 41 sites during the study. Characteristics of local river geometry and flow were measured in order to relate changes in deposits to flows. Surveys of deposits made prior to the study and historical photographs were examined to extend the study results in time and to other sites.

CAMPING BEACHES

Detailed topographic and hydraulic mapping of the channel and flow in the vicinity of 12 of the largest rapids yielded information on the flows required to adjust the coarse debris which forms rapids and on how waves in rapids changed with flow.

HYDRAULIC MAPPING OF RAPIDS

The results of these studies have been published in technical reports which are available from the National Technical Information Service, U.S. Department of Commerce. A list of these technical reports is provided at the back of this document. Information from the technical reports has been combined and summarized in the three Subteam Reports which are provided as appendices to this document. The Sediment, the Biology, and the Recreation Subteam Reports each give more detail on the individual technical studies

RESULTS PUBLISHED

PUBLIC ACCESSIBLE

than is given in the main body of this report. The Dam Operations Summary provides additional background on the current operating criteria for Glen Canyon Dam. A glossary can be found at the back of this document.

SECTION II: MOTIVATION AND BACKGROUND FOR THE STUDIES

Valued Environmental And Recreational Resources Exist Below Glen Canyon Dam

A great many people from around the country and the world are concerned about the resources along the Colorado River below Glen Canyon Dam. Each year, more than 10,000 anglers fish for trophy-size rainbow trout in the 15-mile reach below the dam. Additional anglers fish for trout along the Colorado River and its tributaries in Grand Canyon. Another 9,000 visitors annually take half-day raft tours of Glen Canyon in this reach. An additional 15,000 individuals take white-water float trips through the Grand Canyon each year. Many more people would like to take these trips, but the NPS limits the number in order to protect the environment.

The Colorado River in the Grand Canyon supports an unusual and important community of plants and animals. In the desert Southwest, streamside (riparian) ecosystems are scarce and decreasing in extent along most rivers. In contrast, the Colorado River gorge in Grand Canyon is a protected 277-mile corridor within which riparian vegetation has increased in area since 1963, the year Glen Canyon Dam was completed. The river itself provides habitat for the largest remaining self-sustaining population of humpback chub (a federally-listed endangered species) as well as several other species of native fish.

Flow In The Colorado River Through Glen And Grand Canyons Is Controlled By Glen Canyon Dam

Glen Canyon Dam impounds the water of the Colorado River forming Lake Powell, one of the largest reservoirs in the western United States. By storing and regulating the waters from the Upper Colorado River Basin states of Colorado, Wyoming, New Mexico, and Utah, Glen Canyon Dam enables delivery of water each year to Arizona, Nevada, California, and Mexico, as required by the laws and agreements regulating the management of the Colorado River (Law of the River). Glen Canyon Dam is also a major producer of electricity for the western United States. Its average generation of 4.4 billion kilowatthours produces approximately $80 million annually in gross power revenues (Source: Colorado River Basin Annual Operations Reports 10 through 15).

Of the accumulated legislation and agreements that define the operation and management of the Colorado River, the primary legal mandates include:

- Colorado River Compact of 1922
- Boulder Canyon Project Act (45 Stat. 1057)
- Upper Colorado River Basin Compact (63 Stat. 31)
- Water Treaty of 1944 with the United Mexican States (Treaty Series 944, 59 Stat. 1219)
- Colorado River Storage Project Act (Public Law 84-485)
- Colorado River Basin Project Act (Public Law 90-537)

Fluctuating Releases From The Dam Caused Public Concern

The powerplant at Glen Canyon Dam is designed to be operated as a multiple-use facility capable of baseload and peaking power operation. Glen Canyon Dam can vary the release of water on a daily, monthly, and seasonal basis to produce electricity when it is most needed and its economic value is greatest. For example, it is not uncommon for flows to be varied from 5,000 cfs to 30,000 cfs in a day. This causes the river level to change by 7 to more than 13 feet, depending upon the width of the river and distance downstream of the dam.

Fluctuating releases associated with peaking power operations have caused concern among river users, primarily those who fish in Glen Canyon and who take white-water raft trips in Grand Canyon, and among environmental groups concerned about possible detrimental effects on downstream riparian and aquatic habitats.

Public concern is centered on the impact of dam operations on:

- the quality and safety of fishing in Glen Canyon
- the quality and safety of white-water boating
- erosion of beaches in the Grand Canyon
- terrestrial vegetation and wildlife
- endangered and common native fish species

These concerns were expressed most forcefully during two BOR studies of possible increases in peaking power generation at Glen Canyon Dam. The studies were made to determine costs and benefits of (1) adding one or more generators at Glen Canyon Dam (the "Peaking Power" study) and (2) increasing the capacity of the existing generators (the "Uprate and Rewind" study).

Either of these actions could affect the daily fluctuation in dam releases. Implementation of the Uprate and Rewind Program would increase peak powerplant releases only from 31,500 cfs to 33,100 cfs, whereas the Peaking Power Program would raise peak releases to about 40,000 cfs. Adverse public reaction to the Peaking Power proposal led to its termination in 1980.

BOR published an environmental assessment in December 1982 of the impacts of the Uprate and Rewind Program. No significant impact of increasing the peak powerplant capacity from 31,500 to 33,100 cfs was found, but the close association in time with the Peaking Power study tended to blur the separate issues in the public's mind and again provided a focus for existing concerns about impacts of current operations.

The BOR proceeded with the Uprate and Rewind Program for the generators at Glen Canyon Dam, but agreed not to use the increased powerplant capacity to exceed powerplant release of 31,500 cfs until a more comprehensive study of the impacts of historic and current dam operations was completed.

Large Releases From Glen Canyon Dam Are More Common Since The Filling Of Lake Powell And Are A Cause Of Public Concern

From the start of flow regulation in 1963 until the filling of Lake Powell in 1980, releases generally stayed between 1,000 cfs and 31,500 cfs. Higher releases were very rare. Although the dam produced fluctuating flows which recreationists found undesirable, it also eliminated the very large spring and summer floods which had annually scoured Glen and Grand Canyons. Pre-dam peak flows averaged 93,400 cfs (1921-1962), and reached approximately 300,000 cfs (July 7, 1884). The elimination of annual flooding allowed a much more diverse and extensive riparian vegetative and wildlife community to colonize the old "flood zone" along the river.

However, when Lake Powell filled in 1980, the capacity of the reservoir to store unusually high spring runoff was severely reduced, leading to the current situation in which "flood" releases (over 31,500 cfs) are more common. Concerns were raised over the effect of these flood releases on sediment deposits and vegetation in the river corridor, aquatic and terrestrial wildlife, and on the quality and safety of river recreation. Concern over the short- and long-term impact of these large releases provided another focus for the study.

Reduced River Temperature Resulting From Construction Of Glen Canyon Dam Diminished Habitat For Humpback Chub

On May 25, 1978, FWS concluded that construction and operation of Glen Canyon Dam had jeopardized the continued existence of humpback chub by reducing water temperature and changing the aquatic system. They also concluded that dam operations were limiting the potential for recovering humpback chub, Colorado squawfish, bonytail chub, and razorback sucker. Because little information was available on habitat needs of these fishes, the FWS was unable to recommend any changes in dam operation which would aid recovery of the fish. Additional study was therefore requested.

Our Understanding Of The Relationships Between Dam Operations And Downstream Resources Is Not Complete

The GCES occurred at a critical juncture in the history of Glen Canyon Dam, when significant releases above powerplant capacity were occurring with regularity for the first time. When Lake Powell filled in 1980, a 17-year period with virtually no releases over 31,500 cfs came to an end. Because the reservoir no longer had a vast amount of unfilled space to store spring runoff, the likelihood of releases exceeding powerplant releases in spring and early summer increased substantially.

The filling of the reservoir corresponded with years of unusually high basin runoff in 1983 through 1986. This combination of events led to the flood releases seen in five of the past seven years. Figure II-1 shows how dam releases changed beginning one year before start of the GCES and continuing through to near the end of the study. Operations, the physical and biological environment, and recreational users were all adjusting to this changing situation throughout the study period.

Flows during the study period varied considerably and included flood flows, flows of less than 5,000 cfs, nearly steady flows, and fluctuating flows. Low to medium flows were uncommon during the study period (Table II-1). Most flows were at the high end of powerplant releases. Although 31 percent of the days during the study had flows which fluctuated more than 10,000 cfs during a 24-hour period, this generally occurred before field work for most studies had begun, or were at times not seasonally important for the studied resources.

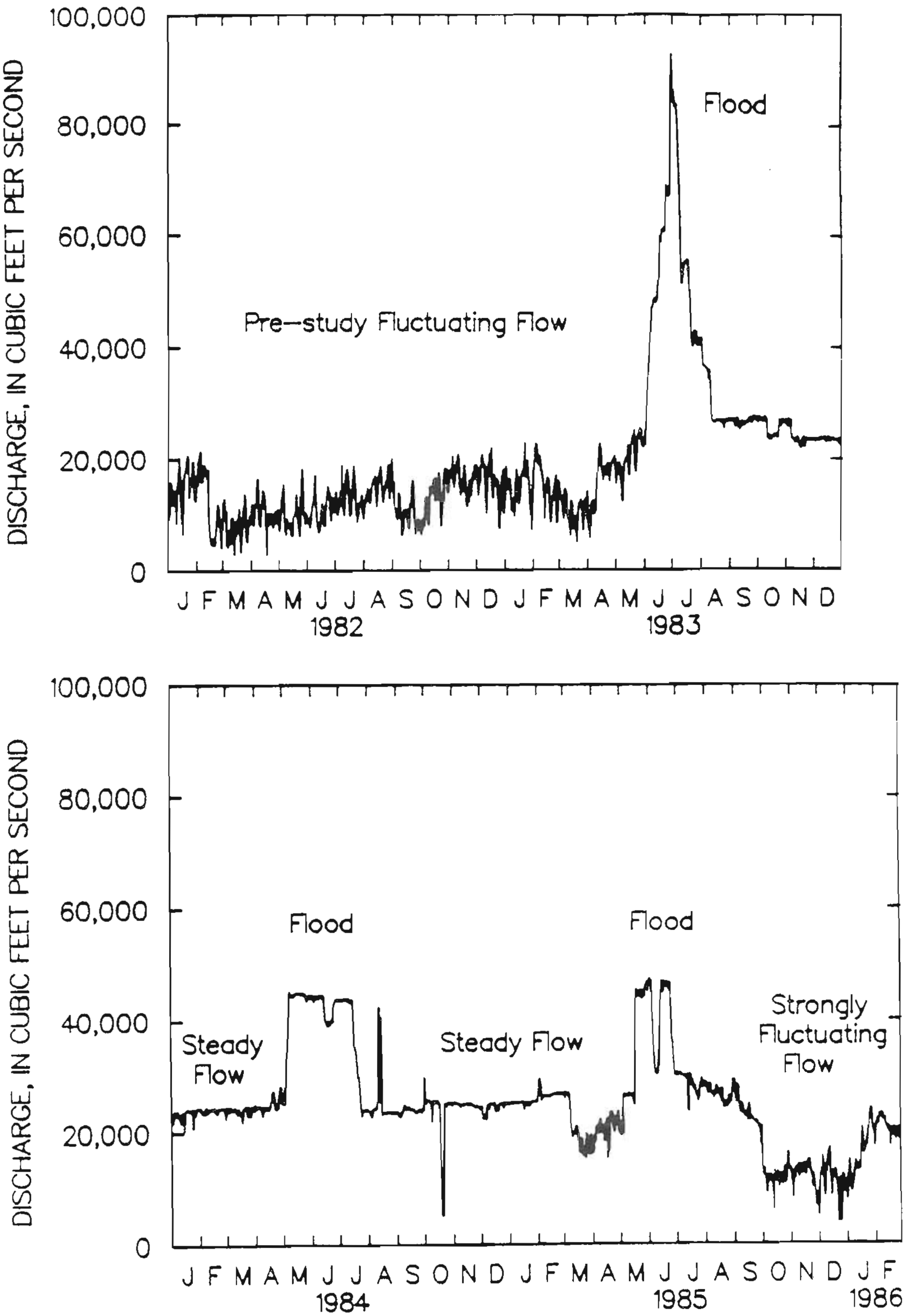

Figure II-1. The GCES occurred (1983-1986) during a transition from nearly continuous fluctuating flows to more frequent steady, high releases and flood releases.

Table II-1. Flow distribution during the GCES study period and the Lake Powell filling period (based on hourly flow data from Glen Canyon Dam).

	Study Period (1983-1986)	Filling Period (1963-1980)
Flow in cfs		
less than 10,000	4	43
10,000-16,000	7	27
16,000-31,500	71	30
31,500-48,000	13	0
over 48,000	5	0
Fluctuations greater than 10,000 cfs	31	77

The results of the GCES must be evaluated with an awareness of the uncertainty induced by a short study period and the limited range of flow conditions available during that period. Also, because few data were available from the pre-dam period or from the post-dam period prior to 1983, our understanding of the initial adjustment of resources to dam operation and status of resources prior to GCES is limited. The GCES also spanned a period of change in dam operations, which further restricted our ability to predict future conditions from past trends. Our projections of long-term system responses have necessarily been based upon study of a limited number of sites over a relatively short period of time. Nonetheless, we believe that collection of data at more locations over a longer time period would not change the major conclusions that (1) dam operations affect downstream resources, and (2) modified operations would better protect selected environmental and recreational resources. Additional data collection, however, would permit us to refine our estimates and increase the certainty of our forecasts.

SECTION III: SETTING AND RESOURCES STUDIED

Below Glen Canyon Dam, the Colorado River passes through the Glen Canyon National Recreation Area (Glen Canyon). In this 15-mile reach of river between Glen Canyon Dam and Lees Ferry can be found one of the finest trout fisheries in the western United States. Below Lees Ferry, the river enters Grand Canyon National Park (Grand Canyon), with its world-famous scenery and white-water rapids (see location maps in Figures I-1 and I-2).

Study Targeted Critical Resources

Agencies and individuals involved in the GCES, working together, identified and selected for study the downstream resources that were both important to the agencies and the public and likely to be affected by dam operations. These are termed the critical resources. Although analyzed independently in the studies, related critical resources have sometimes been grouped here for ease of discussion.

The Critical Resources Are Humpback Chub, Common Native Fish, Rainbow Trout, Camping Beaches, Riparian Vegetation And Wildlife, White-Water Boating, And Trout Fishing

Humpback chub. Humpback chub use the warm, highly saline waters of the Little Colorado River to spawn and rear larval young (Figure III-1). This is the only breeding population of humpback chub in the Colorado River Basin below Glen Canyon Dam. Chub are afforded legal protection through the Endangered Species Act, which assures that no federal action can be taken which would affect critical habitat of the species or jeopardize its continued existence. Further, all federal agencies are directed to use their authorities to help improve the status of the species (exceptions to this are possible under the law but have never been granted).

Common native fish. Eight native fish species inhabited the pre-dam Colorado River and its tributaries. Of these, only endangered humpback chub and three common species (bluehead sucker, flannelmouth sucker, and speckled dace) can still be found in the Colorado River below Glen Canyon Dam. (A very small population of razorback suckers may still exist; however, only one individual of this species was found during the three-year study.) Backwaters, protected areas away from the influence of main channel currents, serve as rearing habitat for native fish (Figure III-1).

Rainbow Trout. Introduced trout have created an important fishery in Glen Canyon. Maintenance of this trout fishery under present management guidelines requires supplemental stocking, without which catch and harvest rates could not be maintained. Rainbow trout spawning occurs on gravel bars in Glen Canyon and represents 28 percent of the average trout harvest.

Camping beaches and other sand deposits. Many of the critical resources mentioned here depend upon the existence of camping beaches and other sand deposits in Grand Canyon. In narrow sections of the river, such deposits were scarce even before dam construction, and campsites along these reaches are still small and widely separated. Sand is more commonly deposited in wider reaches, providing larger and more plentiful campsites.

The largest sand deposits occur where tributaries to the Colorado River within Grand Canyon create debris fans which extend out into the canyon floor, constricting the river and forming rapids. Below the rapids the river widens and forms recirculating eddies of lower velocity where the sand is deposited. Eddies provide relatively quiet water for fish and for mooring boats. Sand deposits within and beside the eddies provide substrate for riparian vegetation, including dense stands of tamarisk and small cattail marshes, as well as camping beaches for boaters (Figure III-1).

Terrestrial riparian vegetation and wildlife. The rich mix of native and exotic streamside vegetation along the Colorado River in Glen and Grand Canyons is widely used by both wildlife and recreationists. The dense post-dam zone of native and exotic plant species near the water's edge has added new diversity to the riparian ecosystem by providing nesting sites for birds and food and cover for other wildlife (Figure III-1).

Riparian birds in particular have increased in both number and diversity. Nesting riparian birds were used in this study to indicate how terrestrial wildlife responds to changes in vegetation. Birds are directly dependent on the quality and extent of riparian vegetation, and pre-1983 data were more available for birds than for other Grand Canyon terrestrial vertebrates.

Grand Canyon white-water boating. The Colorado River through Grand Canyon is one of the finest stretches of white-water in the world. The rapids and the magnificent scenery make these white-water trips (which can last as long as 30 days) a once-in-a-lifetime experience. Boaters spend their day running the big rapids, floating calm stretches of the river between towering walls, hiking side canyons, and visiting special natural and archeological sites. Camps are usually made on sand beaches, which provide the most desirable camping locations along the river (Figure III-1). Reservations for commercial trips, which constitute about 85 percent of the total, are usually made one year in advance. Individuals may wait up to five years to obtain a permit for a private trip.

Trout fishing. Over the past 20 years, the trout fishery has received national prominence. The average size of fish caught peaked in 1980 and use of the fishery peaked in 1983 at over 52,000 users. Due to the popularity of the fishery and increased fishing pressure, more restrictive fishing regulations were introduced in 1978, 1980, and 1986 by AGF to reduce the fish harvest.

SECTION IV: CHANGES SINCE DAM CONSTRUCTION

Dramatic changes have taken place in Glen and Grand Canyons since Glen Canyon Dam was completed in 1963. Impoundment of the Colorado River and flow regulation have changed the magnitude and timing of river flows, the amount of sediment carried by the river, and the temperature of the water. This, in turn, has substantially changed the downstream riverine environment and associated recreation.

Pre-Dam River Flows Had Wide Seasonal Variations In Magnitude, Sediment Load, And Temperature

Pre-dam river flows were characterized by low flows in fall and winter and floods in spring and summer. Spring floods from snowmelt runoff reached a peak in June, and ranged from 25,300 to 300,000 cfs. From 1922 to 1962, the annual volume of flow past the USGS gaging station at Lees Ferry averaged 11.7 maf and ranged from 2.5 to 19.2 maf. In 1953, a typical low-water year (8.79 maf), flow was above 31,500 cfs from late May until the end of June, with a peak of about 70,000 cfs. For most of the rest of the year, flow was very low--typically in the range of 3,000 to 8,000 cfs (Figure IV-1).

In 1957, a typical high-runoff year (17.3 maf), flow reached 126,000 cfs and was above 31,500 cfs from the beginning of May until early August. Except for short periods of tributary flooding, flow was in the range of 5,000 to 10,000 cfs for the rest of the year. Change in discharge during any given day was small.

Annual suspended sediment load past Lees Ferry averaged 65.4 million tons in the period 1948 to 1962, about four to five times the average annual suspended sediment load delivered to the river by the three major tributaries below Lees Ferry. The amount of sediment carried in the river increased during the high flows of snowmelt runoff, but typically reached highest values during tributary floods in the late summer. Sediment carried by the river was sufficient to replenish beaches scoured by spring floods.

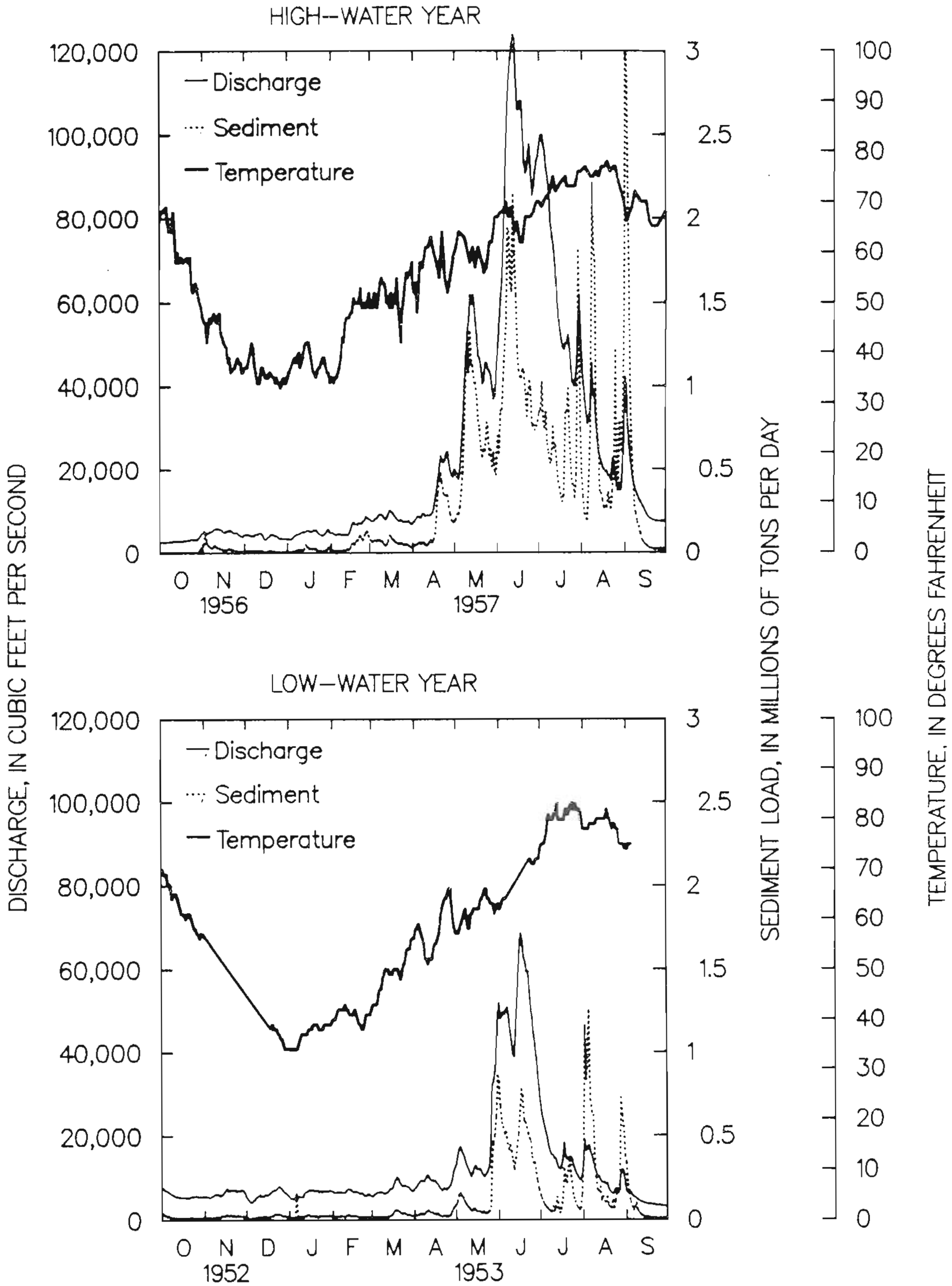

Figure IV-1. Mean daily discharge, total daily sediment load, and mean daily water temperature from low- and high-water years **prior** to dam construction, measured at the U.S. Geological Survey gaging station at Lees Ferry.

Water temperature varied seasonally from near freezing in December and January and reaching a high of near 80 degrees F in July and August. The pattern of water temperatures did not substantially change from year to year even when volume of flow was greatly different.

Post-Dam River Flows Fluctuate Frequently, Carry Little Sediment, And Are Colder

The pattern of post-dam flows is much different. Seasonal changes in flow magnitude, temperature, and sediment load are much less. However, daily fluctuations in flow are much greater. Flow regulation reduced the average annual peak flow from about 93,400 cfs in the pre-dam era (1921-1962) to about 29,000 cfs for the period 1963 to 1980, when Lake Powell was being filled. During a representative post-dam, minimum release year (1982, 8.3 maf) peak flow remained below the powerplant capacity of 31,500 cfs (Figure IV-2). Daily flows were released in response to power demand, changing by as much as 20,000 cfs in a 24-hour period and resembled the pattern of daily releases shown in Figure V-3. Hourly flow was in the range of 16,000 to 27,500 cfs for 25 percent of the year, 10,000 to 16,000 cfs for 34 percent, and below 10,000 for 42 percent of the year. Annual flow volume past Lees Ferry ranged from 2.4 to 20.5 maf.

During the high-water year of 1986 (release volume 16.6 maf), the river outlet works were used to release excess runoff by bypassing the powerplant. Daily flows reached 51,600 cfs (Figure IV-2). Flows exceeded 31,500 cfs for 42 days in May and June. Flows fluctuated during the rest of the year, but remained above 16,000 cfs about 70 percent of the time.

All sediment from upstream of the dam is now trapped in Lake Powell, drastically reducing the sediment load of post-dam flows (Figures IV-1 and IV-2). Annual suspended sediment load at Lees Ferry, which is upstream of any major tributary, is estimated to have been 0.4 million tons in 1982 and 1986, a decrease of about 99.5 percent from pre-dam conditions. Virtually all the sediment added to the system must now be delivered by tributaries below Lees Ferry. (Note the change in the axis scale for sediment between Figures IV-1 and IV-2.)

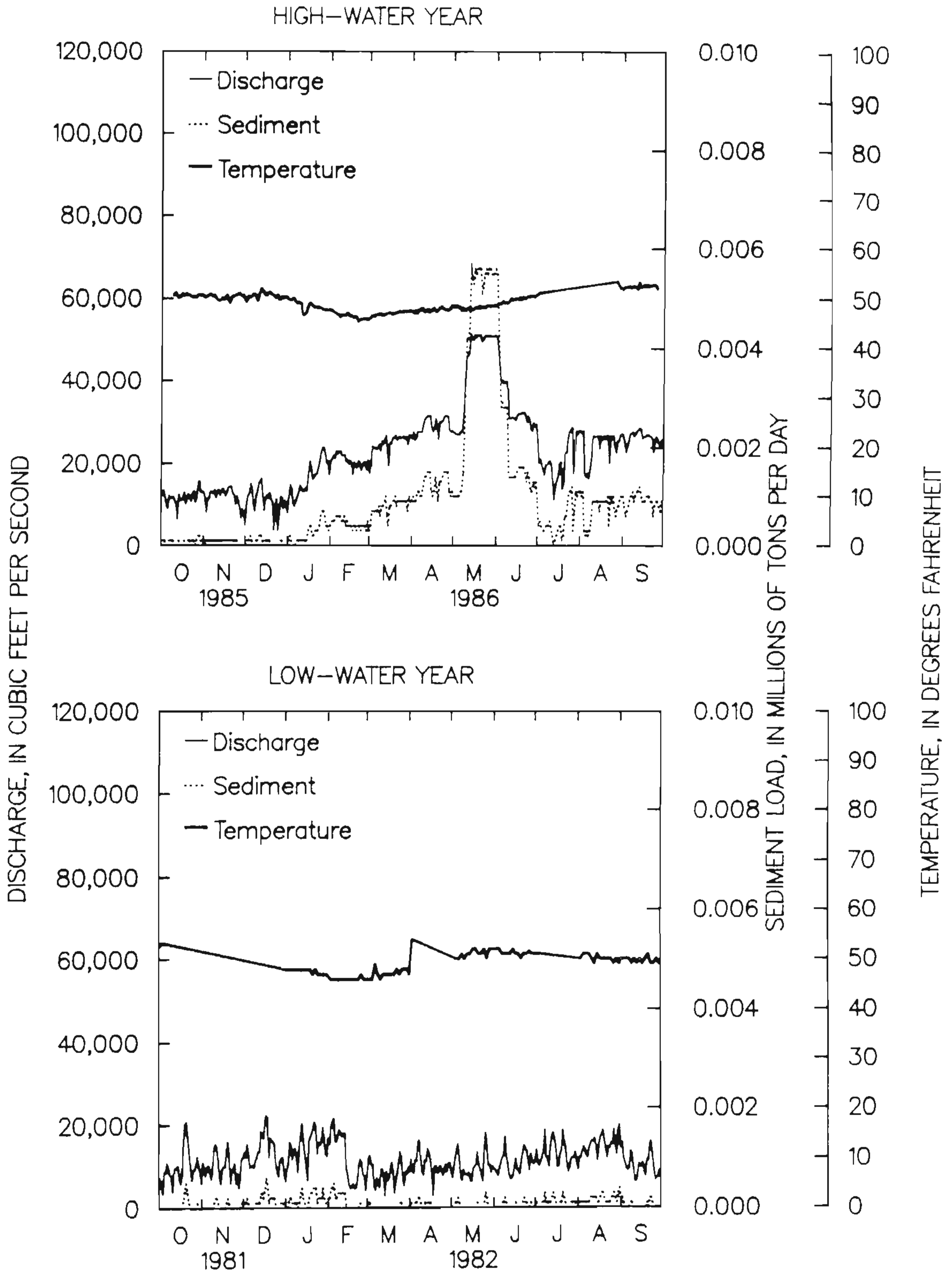

Figure IV-2. Mean daily discharge, total daily sediment load, and mean daily water temperature from low- and high-water years **following** dam construction, measured at the U.S. Geological Survey gaging station at Lees Ferry.

Water temperature no longer changes seasonally but is relatively constant year-round. Water which passes through the powerplant is drawn from a level in Lake Powell where the temperature varies little. River temperature at Lees Ferry now ranges from 46 to 54 degrees F.

Resources Have Changed In Response To Changes In The River

Beaches. Examination of historical photographs shows that locations of camping beaches and sand substrate for vegetation have remained much the same throughout this century. The amount of sand stored in the main channel riverbed appears to have gradually decreased between 1940 and the start of flow regulation in 1963 in response to regional climatic variations. Available evidence is not sufficient to allow us to determine if camping beaches gradually decreased in size during the same time period. Studies of post-dam changes have shown that camping beaches have apparently decreased in area and volume since flow regulation.

Vegetation. The riverbanks which were scoured nearly every year by spring floods are now vegetated (Figure IV-3 and IV-4). Before flow regulation, the vegetation community now called the Old High Water Zone (OHWZ) had stabilized above the level of peak summer floods. The area below this zone was scoured by annual floods and supported only a sparse growth of short-lived herbaceous and shrubby plants. As a result of the decrease in peak flow, significant amounts of vegetation have become established in the former flood zone. This new zone of vegetation is called the New High Water Zone (NHWZ) and is composed of newly-established native species such as willow, seep-willow, and arrowweed; other native species that are colonizing from the OHWZ such as mesquite and acacia; and exotic species such as tamarisk. Tamarisk, a major component of the new zone, was found along the river before 1963, but has greatly increased in area since that time. This increase may not be due entirely to flow regulation--great increases in tamarisk occurred in many riparian zones throughout the Southwest over the same time period. (See Appendix B, Sections II and IV.)

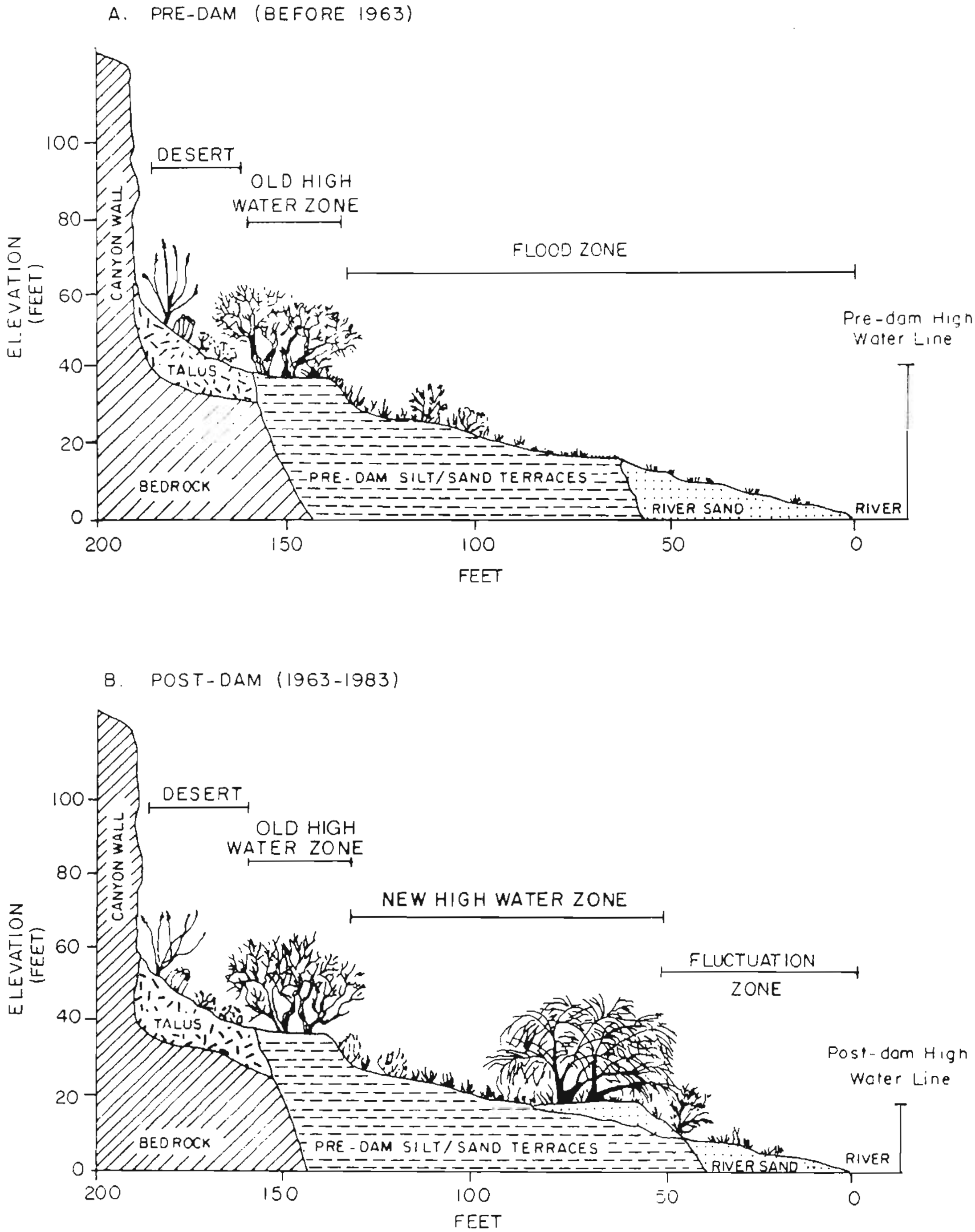

Figure IV-3. Regulation of river flows has significantly changed the distribution of vegetation and sediment along the riverbanks.

The reduction in the annual flood peak also permitted the establishment of marshes in some low, sandy areas along the riverbanks. The increase in area of vegetation along the river, and the addition of new habitats such as marshes, riparian trees, and dense shoreline vegetation, allowed an increase in population densities of a number of wildlife species, including the rare Bell's vireo and willow flycatcher. Also, many birds that did not nest along the river before 1963, now do. (See Appendix B, Sections II and IV.)

Fish. The change from warm, sediment-laden water to cool, clear water has changed the aquatic food base in the river, greatly increasing the supply of algae and associated invertebrates. Trout can now exist in the river due to the lower temperature and sediment concentrations, and they depend on the new food base. However, the cold water has been detrimental to warm-water native fish. Of eight native species originally found in Grand Canyon, only four remain in significant numbers. The spawning area for one of these, humpback chub, is now apparently limited to the Little Colorado River. (See Appendix B, Sections II and IV.)

Recreation. Recreation in Glen and Grand Canyons has greatly increased since completion of the dam in 1963. Today, fishing for trout in Glen Canyon, made possible by the cold water released from the dam, is a major recreational activity generating approximately $0.5 million in recreation benefits* annually.

White-water rafting has grown from fewer than 200 boaters in 1960 to about 16,000 in 1972. Today, white-water boating generates approximately $4 to $9 million in recreation benefits annually, depending upon flow conditions. Although regulation of river flows

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* Recreation benefits were assessed by measuring the "consumer surplus" associated with recreation. Consumer surplus is the amount that recreationists would be willing to pay, beyond their actual expenses, to participate in the activity. This is a standard method of measuring recreation benefits for federal water resource development projects, as recommended by Economic and Environment Principles and Guidelines for Water and Related Land Resources Implementation Studies. U.S. Water Resources Council, 1983. (See Appendix C, Section II.)

and the subsequent lengthening of the white-water season has been a factor in this increase, white-water boating has increased dramatically nationwide during the same period. Other rivers in the United States, both controlled and uncontrolled, have experienced large increases in white-water boating in the last 10 to 20 years. This suggests that white-water boating use of the Colorado through the Grand Canyon would be very high without Glen Canyon Dam, but probably not as high as with flow regulation (Appendix C, Section I).

SECTION V: DAM OPERATIONS

This chapter summarizes the legislated functions of Glen Canyon Dam and how these functions are served through the current operation of the dam. Particular attention is paid to explaining the rationale for the release patterns that have caused concern about downstream impacts--flood and fluctuating releases. More detail can be found in Appendix D, Dam Operations.

Glen Canyon Dam and Lake Powell are part of the 1956 Colorado River Storage Project (CRSP) Act. The original Act included six dams and reservoirs in the Upper Colorado River Basin and eleven participating projects, involving irrigation, industrial uses, and municipal water supplies. Glen Canyon Dam serves the CRSP functions through the storage and release of water from Lake Powell, which has a total capacity of 27 maf. There are three ways to release water from Glen Canyon Dam, as shown in Figure V-1:

(1) Release through the powerplant. Glen Canyon Powerplant has eight generators with a total nameplate capacity of 1,288,000 kilowatts (kW). The combined discharge capacity of the eight turbines is approximately 33,100 cfs. However, a limit of 31,500 cfs (1,900,000 acre-feet monthly) is presently followed. Discharge through the turbines is the preferred method of release because electricity and associated revenue are produced.

(2) Bypassing the powerplant through the river outlet works. The capacity of the river outlet works is 15,000 cfs. The river outlet works are used when there is a need to release more water than can be passed through the powerplant. They are almost always used in conjunction with powerplant releases, producing combined releases ranging from 31,500 cfs to 48,100 cfs.

(3) Spillway releases. Releases through the spillways bypass both the powerplant and the river outlet works. The combined capacity of both right and left spillways is approximately 208,000 cfs. Spillway releases are made only when there is an urgent need to release large volumes of water to avoid overtopping the dam, or to lower the level of Lake Powell. Spillway releases are avoided whenever possible due to the shorter service life of the spillways compared to the other release structures. This brings the total release capacity from all structures to approximately 256,000 cfs.

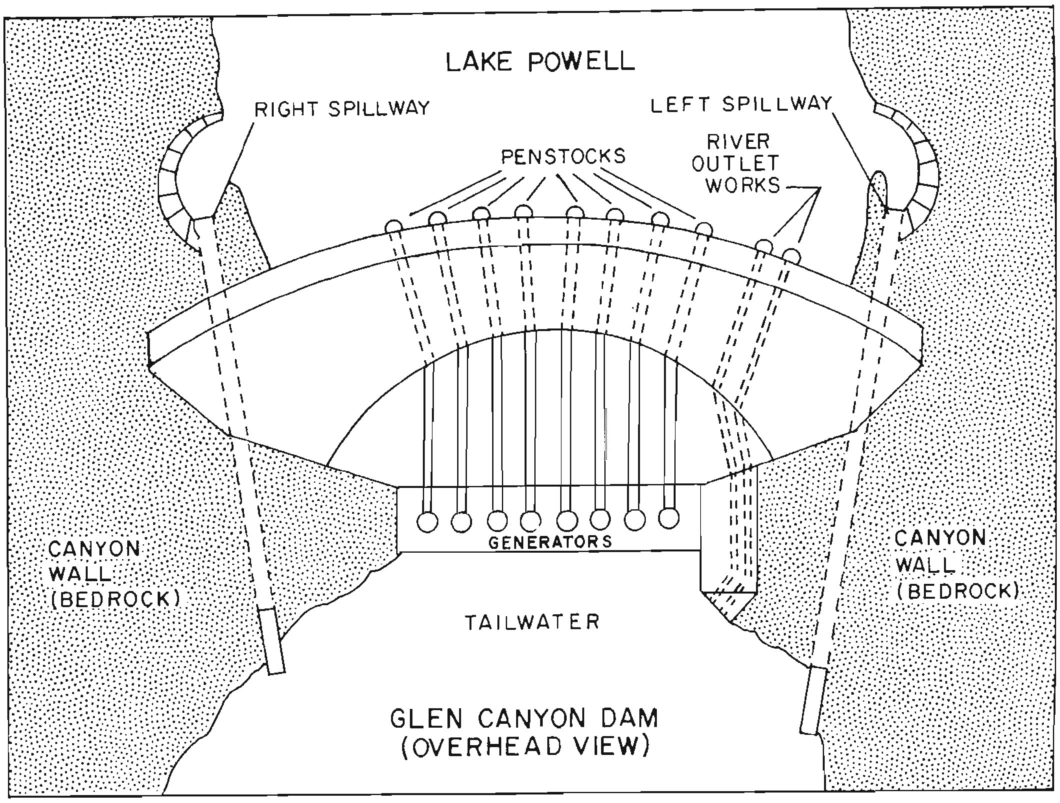


Figure V-1. Water is released from Lake Powell through the powerplant, the river outlet works, or the spillways.

The Major Operational Goal For Glen Canyon Dam Is Water Storage And Delivery To The Lower Basin

Two of the objectives identified in the legislation authorizing the CRSP are most pertinent to the operation of Glen Canyon Dam: (1) providing water storage and regulation for irrigation and beneficial consumptive use, and (2) satisfying water delivery requirements to the Lower Basin, as defined in the Colorado River Compact. All other project purposes, including the generation of hydroelectric power, are incidental to these goals.

The primary purpose of Glen Canyon Dam in the CRSP is to enable the states of Utah, Colorado, Wyoming, and New Mexico to utilize their apportionment of Colorado River water and meet their obligations for water delivery to the states of Arizona, Nevada, and California. The reservoir (and others in the CRSP system) allows the Upper Basin states to take water year-round from the Upper Colorado River for consumptive uses and still store enough spring runoff in Lake Powell to guarantee the required delivery to the Lower Basin even during a long period of drought.

The Operating Criteria, administered by the Secretary of the Interior, define the minimum annual release objective to the Lower Basin to be 8.23 maf. Releases greater than 8.23 maf annually are permitted if the storage in Upper Basin reservoirs is greater than that required by section 602(a) of the Colorado River Basin Project (CRBP) Act. To the extent necessary, releases can be made to accomplish specific objectives identified in the Operating Criteria. A more definitive description of the Operating Criteria is given in Appendix D.

<u>Objective release of 8.23 maf.</u> Glen Canyon Dam is operated such that an objective of 8.23 maf is released to the Lower Basin each year (monthly distribution of volume is not specified). If this release cannot be met by the CRSP system of reservoirs, the Upper Basin water users may curtail water use sufficiently to allow this delivery.

<u>Meeting "602(a)" storage requirements.</u> Section 602(a) of the Colorado River Basin Project (CRBP) Act requires

that the system of reservoirs in the Upper Basin annually achieve water storage sufficient to make the objective 8.23 maf delivery to the Lower Basin without impairing Upper Basin uses. As the largest CRSP reservoir, Lake Powell must annually contribute the major share of storage toward this goal. The Secretary of the Interior is required annually to prepare a plan of operations for the CRSP reservoirs which specifies the amount of storage required by September 30 to meet the "602(a)" requirement. However, to date no official specification of the amount of storage required has been made. Instead, each year the annual operating plan contains a statement that the "active storage in Upper Basin reservoirs forecast for September 30, 19..., exceeds the '602(a)' storage requirement under any reasonable range of assumptions ... Therefore, the accumulation of '602(a)' storage is not the criterion governing the release of water during the current year." The role of "602(a)" storage in determining the operating level of Lake Powell will be discussed further below.

<u>Maintaining Lake Mead storage equal to or greater than Lake Powell storage.</u> In order to ensure that Colorado River Basin water supplies are apportioned equally between the Upper and Lower Basins, the CRBP Act stipulates that releases from Lake Powell will be made to maintain, as nearly as practicable, an amount of storage in Lake Mead equal to that in Lake Powell. Equality of storage also affords approximately equal power head at Hoover and Glen Canyon Powerplants.

<u>Avoiding spills (flood releases).</u> Releases can be made from Lake Powell to avoid spilling, that is, to avoid having to release water in any way other than through the powerplant. This means that powerplant releases can be increased at any time (within generator capacity) to avoid having to make non-powerplant releases later.

In addition to the primary objectives of water storage and water delivery, several incidental objectives exist for the operation of the Colorado River dams as defined in the Operating Criteria. These incidental objectives include: (1) power production, (2) flood control, (3) river regulation, (4) water quality control, (5) recreation, (6) enhancement of fish and wildlife resources, and (7) enhancement of other environmental factors.

Power production: This function has a substantial effect on the daily operation of the dam but, as described above, it is not allowed to interfere with the primary functions of water storage and delivery. The other incidental objectives do not significantly drive the operation of the dam, but are addressed when they will not interfere with the primary functions.

Flood control: Existing space at Lake Powell can be used as credit toward the 1.5 maf of space which must be reserved at Lake Mead for flood control. There are, however, no specific flood control requirements at Lake Powell.

River regulation and water quality: Glen Canyon Dam has not been used significantly for river regulation or water quality control.

Recreation: Summertime releases are kept above 3,000 cfs for white-water rafting.

Fish, wildlife, and other environmental factors: Winter releases are kept above 1,000 cfs. (During the Lake Powell filling period, special releases were made for a time to enhance the habitat for bass in Lake Mead. Eventually, those releases were ruled to be interfering with water conservation principles and were ended.)

Flood Releases Are A Function Of Reservoir Level Targets, Uncertainty In Runoff, And Operating Rules For Handling Increases In Forecast Runoff

Under current operations, the annual risk of making flood releases is estimated to be about one in four (Appendix D, Section III). Several factors influence the frequency of flood releases.

The dam is operated to address two goals: (1) maximize water storage for later delivery, and (2) minimize the magnitude and frequency of flood releases. These goals conflict with each other, because it is not possible to increase storage without increasing the risk of flood releases. This occurs because reservoir inflows cannot be perfectly predicted. The closer reservoir levels are brought toward full capacity during the year, the more likely it is that unanticipated inflows will require flood releases. Conversely, avoiding flood releases by lowering the filling target for the reservoir increases the likelihood that unexpected shortfalls in runoff, or long periods of drought, will leave the reservoir with too little stored water to meet all water demands.

Reservoir target levels for annual operations. Operations are planned each year to have 22.6 maf of usable storage (reservoir elevation 3,684.6 feet [ft]) on January 1, and have the reservoir full (elevation 3,700 ft) on July 1.

The July target to fill the reservoir is not specified directly in the CRSP Act or in other regulations. Because there are areas of uncertainty regarding the quantification of "602(a)" storage, a practical solution to the question of minimum storage has been to fill Lake Powell each year, if possible. Thus, while a strict quantification of "602(a)" storage does not control the release of water from CRSP reservoirs, the uncertainty over the magnitude of "602(a)" storage has led to informal operating criteria which substantially affect dam operations.

Uncertainty in annual runoff. The schedule of monthly releases during the spring runoff period from January through June is designed to result in a full reservoir by July 1, with all releases being made through the powerplant. Any increase in inflow above the forecast may result in flood releases at some point during the spring runoff. The design of the release schedule depends critically upon the forecast of the annual inflow.

However, the total annual inflow is difficult to predict. For example, since 1922, the annual runoff in the Upper Basin has ranged from 2.5 maf to over 20.0 maf. Because of this uncertainty, updated forecasts of runoff are made each month and the monthly release schedules adjusted. Early in the annual runoff period, the potential error in the forecast of the total runoff is very large. Due to the variability in climatic conditions, and modeling and data uncertainties, these forecasts could have a large error. Figure V-2 shows how the error, above and below the projected total runoff, is typically reduced each month as forecasts are updated based on information about the actual runoff.

Operating procedures for handling increases in forecast runoff. Under current operating procedures, any increase in the forecast runoff volume is spread evenly over the months remaining in the runoff period rather

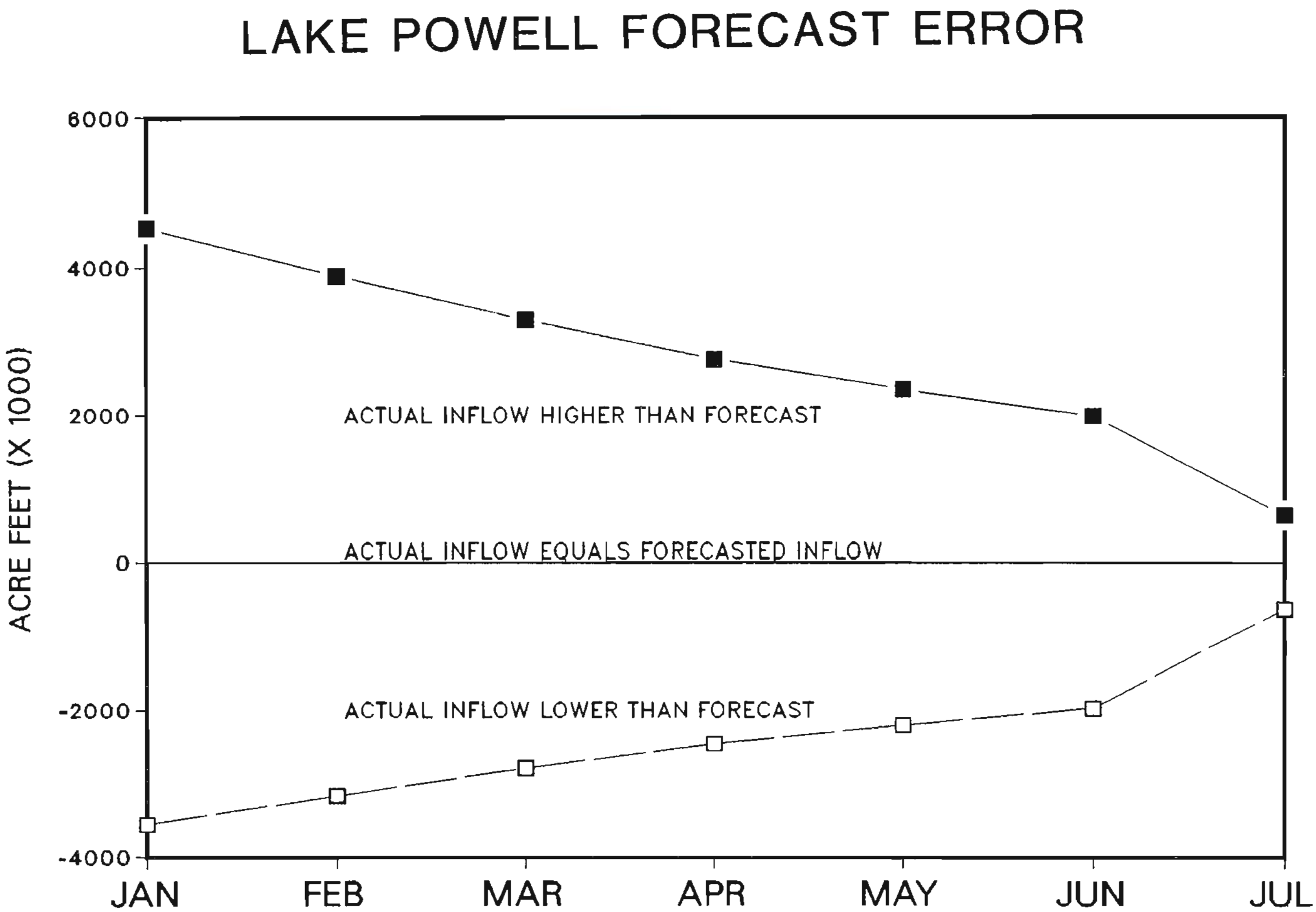


Figure V-2. The forecast error for the total annual inflow into Lake Powell is reduced as the actual runoff progresses.

than released immediately by increasing releases to maximum powerplant capacity until the excess volume is passed. This is done to guard against making an unnecessary release of water should the projected increase not materialize. This procedure does, however, increase the risk of flood releases during the peak of the runoff.

Fluctuating Releases Are Made To Match Electricity Production To Demand And To Sell The Most Power

The Western Area Power Administration (WAPA) markets and transmits the power generated at Glen Canyon Dam and other federal facilities. The marketing of power, and the factors that shape the demand for and production of power at Glen Canyon Dam are many and complex. Refer to Appendix D for a more complete description.

The CRSP Act directed that Glen Canyon Dam be operated to produce the greatest practical amount of power that could be sold at firm power and energy rates (long-term contracts for guaranteed supply). Power produced at Glen Canyon Dam provides electricity and helps to repay the cost of facilities and projects associated with the CRSP. Revenues collected from the sale of the power, municipal and industrial water supplies, and irrigation water are applied to the Upper Colorado River Basin Fund, established through Section 5 of the CRSP Act. These revenues provide for the repayment of the costs associated with the the initial federal investment, interest, portions of participating irrigation projects, and operation and maintenance functions. Annual repayment studies are made to determine if adjustments in the power rates are required. By law, rates for power generated by the CRSP must be set at the lowest level consistent with sound business principles. Although this means that the CRSP generation facilities cannot be operated "for profit," it does not preclude the generation of surplus annual revenues to be used for anticipated future costs.

Power is produced on a fluctuating (peaking power) basis in order to increase the value of the electricity produced. This is done by releasing water and producing power when power is most needed during the day and its value is highest to consumers--generally in the morning and evening (Figure V-3.) Unlike many types of (non-hydroelectric) power generation facilities, the efficiency of power generation at Glen Canyon Dam is very high over a wide range of powerplant output. The facility can be run at very low and very high output, and output can be increased and decreased rapidly without significantly increasing the costs of electrical generation. This makes it very competitive with other sources of peaking power. The value of the power, and hence the attractiveness of long-term contracts, is increased by scheduling power generation to coincide with peak demand. Producing power in this fashion enables WAPA to sell the greatest amount of power at firm energy rates, as stipulated in the CRSP Act.

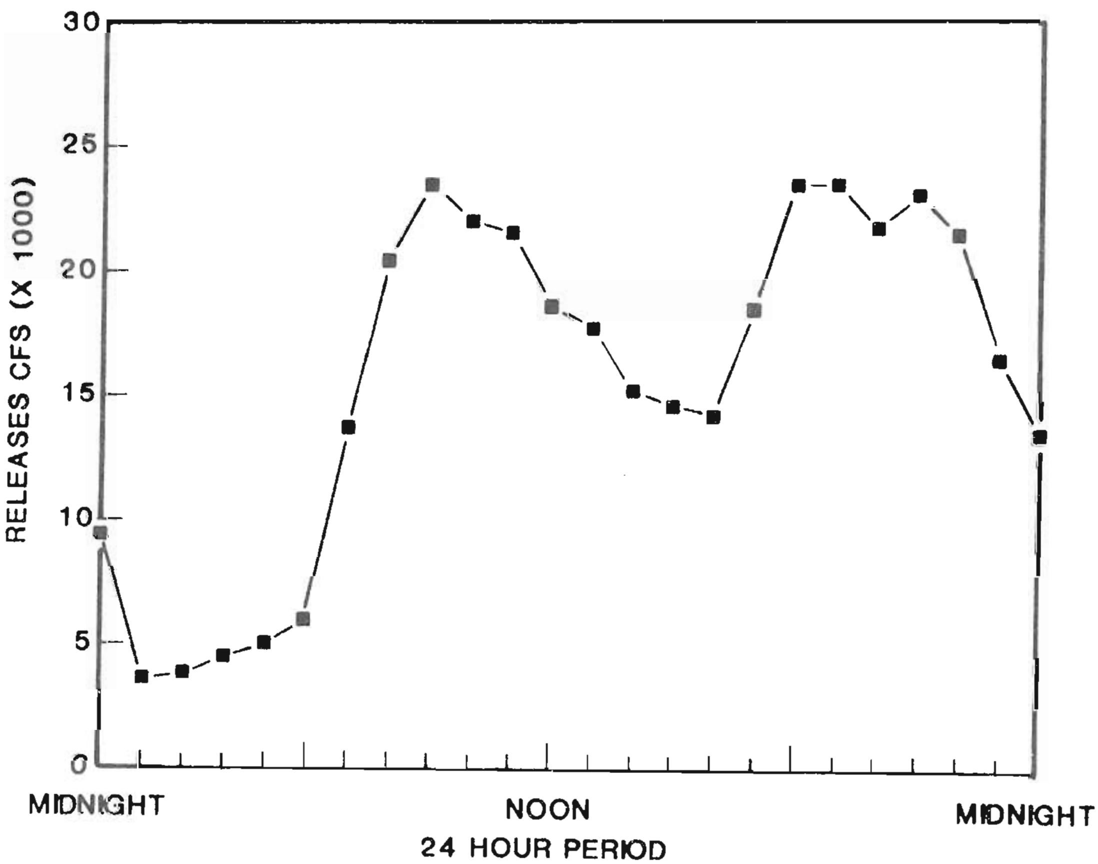


Figure V-3. When operating in a peaking power mode, dam releases increase during periods of high demand (morning and evening).

Summary of Annual, Monthly, and Hourly Operations. The following discussion and Table V-1 summarize the considerations in developing annual, monthly, and hourly water release schedules.

The volume of water released from Lake Powell each month depends on the forecasted inflow, the annual storage targets, and annual release requirements. Demand for electrical energy is also considered and accommodated as long as storage requirements are not affected. Generally, fall and winter releases are designed to meet the January 1 storage target. January through July releases are scheduled to create space in the reservoir so that the forecasted runoff will not produce spills and will fill the reservoir in July. Spring releases are designed to accommodate the changes in inflow as they occur. July through September releases are used to compensate for any missed targets and to reach the January 1 target of 22.6 maf of storage.

After these considerations have been satisfied, and if there is any flexibility remaining to adjust monthly releases, then seasonal variations in the power demand may be considered. Power demand is highest during the winter and the summer months. Therefore, higher releases to generate more electricity are scheduled in these months whenever possible. Greatest flexibility to match monthly releases to power demand exists in years of moderate runoff and reservoir conditions. If minimum releases are required because of low reservoir conditions or low expected inflow, there remains little flexibility to accommodate changing power demands. Likewise, if the reservoir is near full or the runoff is extremely high, monthly releases are scheduled at or near maximum capacity most of the time, again leaving little flexibility for power generation.

Hourly releases are set to reach the monthly release volumes, to maintain established minimum rates, and to follow the pattern of energy demand. Demand for power may change the rate at which water is released, but it is never allowed to change the monthly volume of release. Minimum releases currently maintained are 1,000 cfs during the winter and 3,000 cfs in summer.

Emergency conditions, such as river search and rescue or failures in equipment, may cause severe departures from expected schedules. Generally these departures are short-lived and the effects on water conservation can be mitigated in a short time.

Table V-1. Decision criteria affecting releases at Glen Canyon Dam.

Annual Targets:

1. Minimum objective annual release of 8.23 maf.

2. If minimum storage requirement (602[a] storage) is met, then releases greater than 8.23 maf may be scheduled for:

   a) Lower Basin consumptive uses.
   b) To equalize storage between Lake Powell and Lake Mead.

Monthly Targets:

1. If reservoir is expected to fill, satisfy annual release objectives by:

   a) Meeting January 1 storage target of 22.6 maf, AND
   b) Meeting July target to fill reservoir, AND
   c) Scheduling releases to avoid anticipated spills.

2. If reservoir is expected not to fill, satisfy annual release objectives by:

   a) Scheduling monthly pattern to meet the minimum 8.23 maf objective, OR
   b) Scheduling monthly pattern to equalize storage between Lakes Powell and Mead.

3. Allow flexibility to provide for a changing forecast.

4. Accommodate seasonal patterns in energy demands if they do not affect annual objectives

Hourly Schedules:

1. Meet monthly targets, AND
2. Maintain minimum release rates (1,000-3,000 cfs), AND
3. Follow hourly energy demands, AND
4. Accommodate emergencies and other unexpected external factors.

SECTION VI: IMPACTS OF CURRENT OPERATIONS

Current Operations Are Characterized By Flood Releases And Fluctuating Releases

Two aspects of current operations have substantial impacts on downstream resources: flood releases and fluctuating releases. This chapter describes the effect of these releases on critical environmental and recreational resources.

Flood releases are defined as releases greater than the designated powerplant capacity which are discharged through the river outlet works and spillways. For the GCES, the maximum powerplant capacity was defined as 31,500 cfs. The river outlet works are generally operated at or near the full capacity of 15,000 cfs. Therefore, releases above powerplant capacity are usually in the range of 40,000-50,000 cfs. Flood releases generally occur for four to six weeks in May or June in years when runoff is well above average or the forecast of runoff is too low. These kinds of releases were very rare prior to the filling of Lake Powell in 1980. Since then, flood releases have occurred in five of seven years. Flood releases are expected to occur in one out of four years assuming full reservoir conditions exist and that future runoff patterns are similar to historic runoff patterns. (See Appendix D, Section III.) A typical flood release pattern (Figure VI-1a) for the 1986 water year shows the high releases in May and June.

Fluctuating releases are made when the dam is being operated to produce peaking power. A typical daily release pattern for peaking power operations is shown in Figure VI-1b. For the purposes of the GCES, fluctuations are defined as a change in dam release greater than 10,000 cfs during a day. This cut-off point, although somewhat arbitrary, is based on changes in flow that appear significant for recreation and the environment. For example, when daily fluctuations are greater than 10,000 cfs, they are noticed by a substantial majority of white-water boaters. Also, in practice, when releases are fluctuating, the fluctuations are almost always greater than 10,000 cfs.

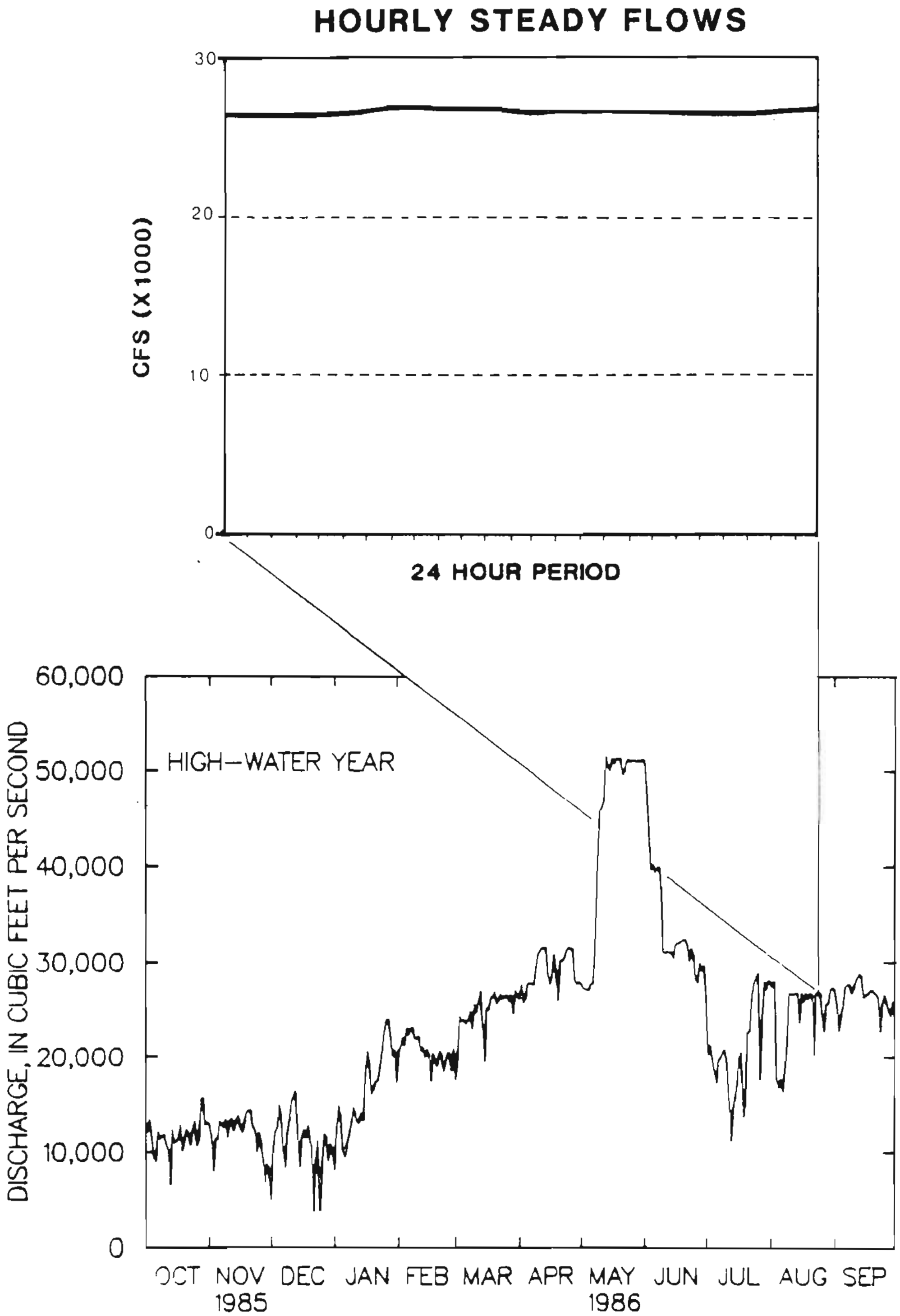


Figure VI-1a. The releases for 1986, a high-water year, were used in the study to represent current operations. Mean daily discharge for water year 1986 and hourly releases for August 21, 1986, illustrate high steady flows.

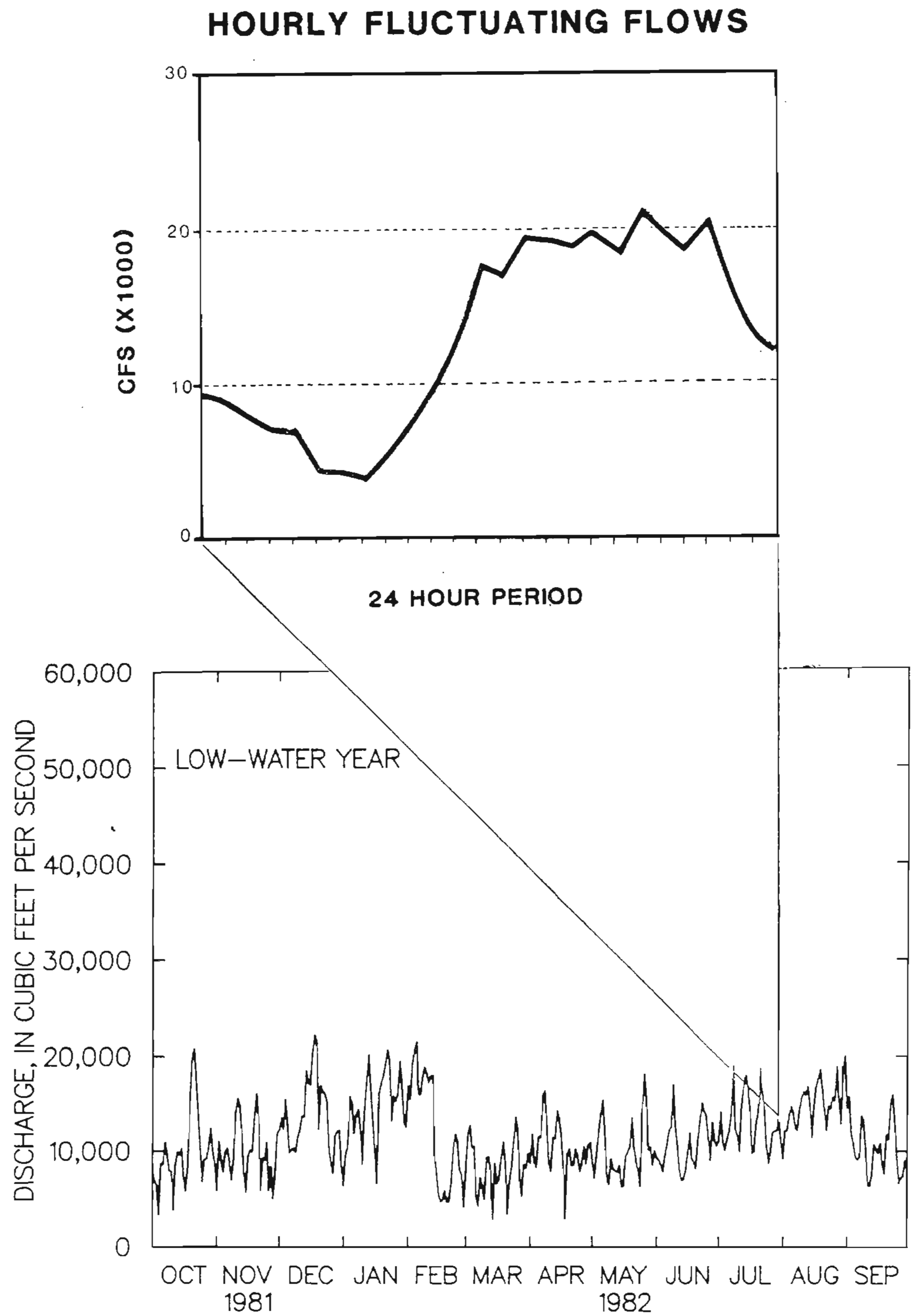


Figure VI-1b. The releases for 1982, a low-water year, were used in the study to represent current operations. Mean daily discharge for water year 1982 and hourly flows for August 4, 1982, illustrate fluctuating flows.

Lake Powell has the water storage capacity necessary to provide the required annual release objective of 8.23 maf even during a long period of drought (Appendix D). Therefore, steady flows lower than than 9,000 cfs are rarely released. Such low flows generally occur as part of a pattern of fluctuating releases for power production. Under existing operations, minimum releases are delivered each year in a pattern of fluctuating releases much like those shown for 1982 (Figure VI-1b).

Definition of Current Operations. To simplify and quantify the pattern of current releases during the GCES, we created a representative sequence of years with three low-water years for every one high-water year (Figures VI-1a and VI-1b). The actual releases of 1982 (8.25 maf) and 1986 (16.6 maf) were selected to represent the low-water year and high-water year, respectively. Each low-water year has year-round fluctuating releases with no spring flood, whereas each high-water year has many months of high steady releases (20,000 to 31,500 cfs), few months of fluctuating releases, and a spring flood release of 40,000 to 50,000 cfs for four to six weeks.

Basis for evaluation of current operations. The effect of flood releases was assessed by comparing the impacts of the current operations sequence described above against the impacts of the same sequence with the spring flood releases removed. In order to keep the annual release volume constant, the flood volume of about 1.0 maf was spread evenly throughout the year, increasing releases slightly (1,000-2,000 cfs). Similarly, the baseline for evaluation of fluctuations was the current operations sequence with all daily fluctuations converted to steady releases with the same daily volume.

The flow sensitive aspect of each critical resource is given in Table VI-1. This table also presents the part of the year (sensitive period) in which the aspect used for evaluation is most affected by flows. For some resources, the sensitive period encompasses the entire year. The measure of the flow sensitive aspect is given in the table as well. For each resource, an increase in the measure corresponds to a positive impact. For example, the flow sensitive aspect for humpback chub is the area available for spawning and rearing in the mouth of the Little Colorado River; the measure is population size, and an increase in population size is a positive impact.

Table VI-1. Basis for assessing the impact of flows on critical resources.

RESOURCE	FLOW SENSITIVE ASPECT	SENSITIVE PERIOD	IMPACT MEASURE
HUMPBACK CHUB	Area of spawning and rearing habitat at the mouth of the Little Colorado River	May to June	Population size
COMMON NATIVE FISH	Number and stability of backwaters	June to August	Population size
TROUT	Spawning in the mainstream and tributaries; mainstream stranding	December to March	Population size
TROUT FISHING	Recreation value of the fishery at Lees Ferry and the probability of accidents	All year	Benefits and safety
VEGETATION & WILDLIFE	The areal extent of vegetation	All year	Areal extent
WHITE-WATER BOATING	Recreational value of the experience and the probability of accidents	May to October	Benefits and safety
BEACHES	Probability of erosion and loss of sediment	All year	Areal extent

In the impact matrices (Figures VI-5 and VI-7) which follow, a "plus" indicates that the critical resource is positively affected by adding flood (or fluctuating) releases to the baseline sequence of years. A "minus" indicates that the addition of floods or fluctuations has a negative impact. A "zero" indicates no significant impact. A "question mark" indicates that the current data are insufficient to judge impacts.

Flood Releases Have Negative Impacts On Terrestrial Resources And Recreation

The flowchart in Figure VI-2 shows the pathways by which flood releases adversely affect the critical resources. As the magnitude, frequency, and duration of floods increase, the impact of floods on resources also increases. These impacts are displayed for each critical resource in the matrix in Figure VI-5.

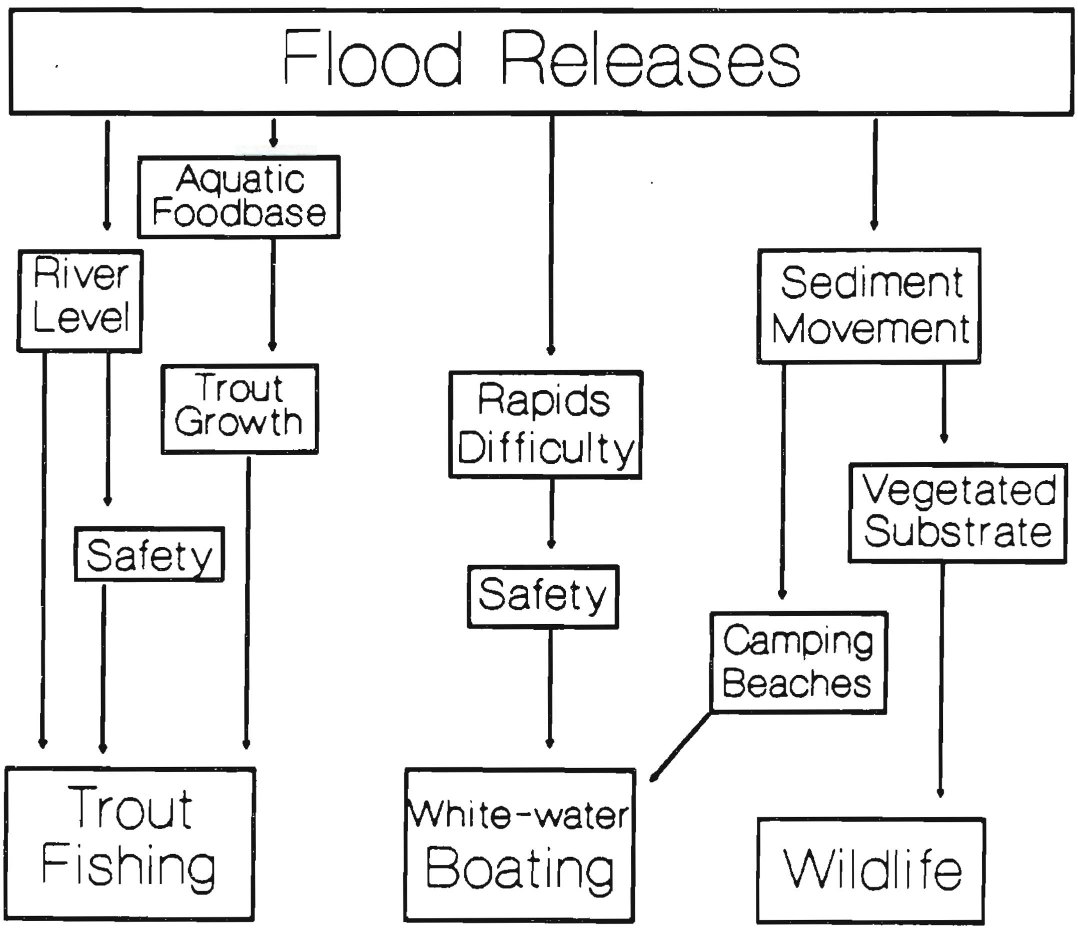
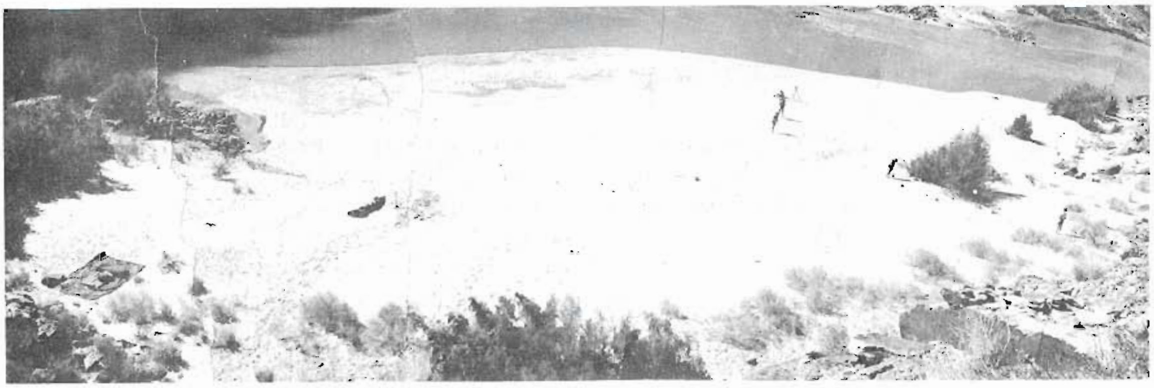


Figure VI-2. Pathways of adverse effects of flood releases on critical resources.

Terrestrial resources. Floods are generally deleterious to downstream resources, but their greatest negative impact occurs to terrestrial resources and recreation. Beach sand is redistributed and may be lost from the system whenever flows inundate areas normally exposed. Although some beaches, especially in wide reaches of the river, may build up as a result of the redistribution of sand, these new deposits are rapidly eroded after flood recession (Appendix A, Section II). Sand deposits used as camping beaches are typically more protected from erosion than other sand deposits. However, loss of sand from less protected deposits may result in gradual loss of camping beaches because these less protected deposits supply sand to replenish camping beach deposits (Appendix A, Section II). As flow increases above 40,000-50,000 cfs, more and more of the beaches protected by debris fans are subjected to erosive downstream flow. At 70,000-90,000 cfs, most sand deposits are subject to direct erosion by downstream flow (Appendix A, Section II). The impact of floods on beaches is greatest upstream of the Little Colorado River, which is the major source of new sand to Grand Canyon. The loss of camping beaches and sand substrate is potentially irreversible because sediment lost to the system during flooding is not quickly replaced by tributary flows.

Recurrent flooding could therefore cause a severe reduction in areas of camping beaches and sand substrate for vegetation in Grand Canyon. Loss of beaches is most severe in the narrow reaches of the canyon where camping beaches are already scarce. An example of how beach deposits and vegetation are inundated by flood releases is shown in Figure VI-3. Photos of a beach deposit prior to and after the 1983 flood releases are shown in Figure VI-4.

Loss of substrate will result in a loss of riparian vegetation because the densest stands of vegetation commonly occur on sand deposits near the water's edge. Vegetation can also be destroyed by inundation, scouring, or burial by redeposited sand. Long-lived terrestrial vegetation therefore cannot become established below the level of the highest frequently recurring flow. At floods of 90,000 cfs, up to 50 percent of the total plant cover may be lost in some areas. Ninety-five percent of the marshes along the river were lost during flooding in 1983-1986. Scouring of marshes was so severe that they may not recover. (See Appendix B, Section V.)



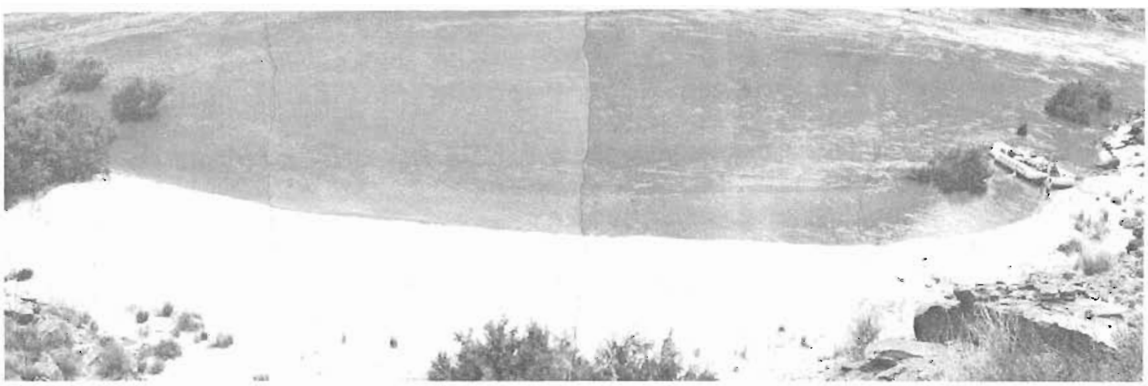


Figure VI-3. Large areas of beach, which are exposed at low flows (top photo, 5,000 cfs, October 1985), are submerged at flood flows (bottom photo, 40,000 cfs, June 1985).

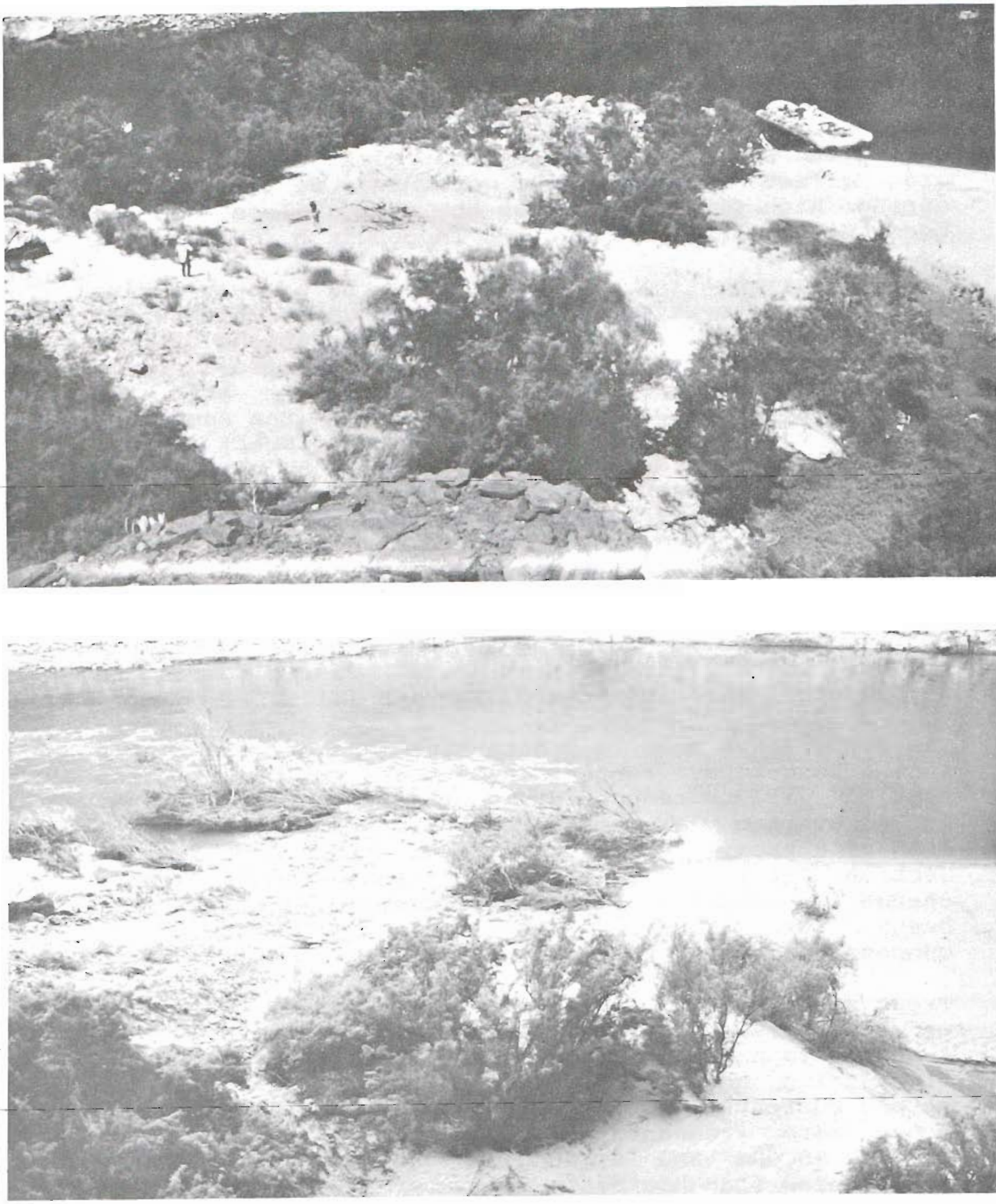


Figure VI-4. Riverbanks, covered with sand and vegetation (top photo), were significantly eroded and stripped of vegetation following the 1983 flood releases (bottom photo).

Wildlife populations which use vegetation for resting, nesting, and feeding will gradually decline in numbers due to the loss of habitat area. Loss of bird reproduction is especially acute if flooding occurs during the spring nesting season. Mammals and reptiles are affected through the drowning of individuals during high flows as well as the gradual loss of numbers through habitat reduction (Appendix B, Section V.)

White-water boating. Floods also have a negative impact on white-water boating. Surveys of white-water guides, NPS accident records, and observations of over 5,000 boats running rapids under different flows, show that flood releases significantly increase both the hazard associated with running rapids and the number of boaters that choose to walk around difficult rapids. For example, at Crystal Rapid, nearly 50 percent of boats have passengers walk at flood flows, compared to 20 percent at flows between 10,000 and 31,500 cfs. The chance of flipping a boat when running a major rapid increases from 3 percent at high flows (16,000-31,500 cfs) to 8 percent at flood flows (31,500-50,000 cfs). In addition, recreation benefits are 17 percent lower for a commercial trip and 45 percent lower for a private white-water trip at 45,000 cfs compared to 30,000 cfs. (See Appendix C, Section III.)

If flood flows lead to substantial loss of beach area in the long-term, recreation benefits for white-water boating will be reduced by approximately 50 percent. In an average year, this reduction could represent a loss of approximately $5.2 million. (See Appendix C, Section III.) This figure represents the potential change in annual white-water recreation benefits from beach loss, and not the potential change in concessionaire revenues.

Trout fishing. Flood releases have negative impacts on trout fishing. At Glen Canyon, fishing boats are required to have a minimum of 25 horsepower motors when flows rise above 40,000 cfs in order to handle the strong currents. Accidents, such as swamping of boats, occur more frequently at flood flows than at flows between 10,000 and 16,000 cfs, the safest flow range for fishing from boats. High water also disperses the fish populations and reduces the probability of a catch. Compared to optimum conditions, which occur at approximately 10,000 cfs, flood flows of 45,000 cfs reduce recreation benefits from a fishing trip by 60 percent. (See Appendix C, Section III.)

Aquatic resources. No direct adverse impacts on adult fishes have been shown to result from spring flood releases. In fact, floods appear to benefit humpback chub. Younger age classes were well represented in humpback chub populations following the recent high-water years of 1984 and 1985, indicating good reproduction in those years. Flood releases from the dam back up flow in the Little Colorado River and form a large lake-like area at its confluence with the Colorado River. This increases the size of the quiet-water habitat required for rearing of larval chub. Once chub reach a size that allows them to survive in the mainstem river, floods have few direct impacts on them. Floods also have few direct effects on common native fishes and trout. Floods do temporarily eliminate low-velocity, nearshore habitat for juvenile trout and common native fish, increasing mortality and energy expended on survival. However, floods do not appear to have long-term effects on the aquatic system. (See Appendix B, Section V.)

IMPACT OF FLOOD RELEASES ON RESOURCES

CRITICAL RESOURCES						
Chub	Native Fish	Trout Repro/Grow	Trout Fishing	W W Boating	Beaches	Terres. Habitat
+	O	O / O	–	–	–	–

Figure VI-5. Flood releases have adverse impacts (-) primarily on terrestrial resources and recreation. They have no significant impact (0) on trout and common native fish, and appear to benefit (+) humpback chub.

Fluctuating Releases Have Negative Impacts On Recreation, Mixed Effects On Aquatic Resources, And Little Effect On Terrestrial Resources

The direct and indirect adverse impacts of fluctuating releases on the critical resources are shown in Figure VI-6. Fluctuations, which can cause the river level to rise and fall by more than 13 feet each day, have the strongest negative effect on white-water boating.

<u>White-water boating.</u> The quality of white-water boating is reduced by fluctuations. Boaters place a high value on the naturalness of the setting for their trip, and the daily rise and fall of the river is seen by boaters as unnatural. Fluctuations also make it much harder to run a trip. Beaches that appear to be good campsites can become submerged overnight as the river rises. Conversely, boats moored during high water can be found the next morning stranded on the beach or rocks, far from the water's edge. Reports of boats being stranded rise from near zero at steady flows to over 13 percent of boaters interviewed during fluctuations. During fluctuating flows, private boaters and commercial guides must choose campsites and moorings very carefully and sometimes have to move boats several times during the night. Trips must be planned carefully to reach critical rapids during favorable water, and delays and crowding at these rapids are common. As a point of comparison, the white-water recreation benefits for a typical low-water year are about $0.8 million higher under steady releases than fluctuating releases. (See Appendix C, Section III.)

Although fluctuations do not have a long-term effect on future recreational <u>opportunities</u>, the immediate reduction in the quality of white-water boating trips is in a sense irreversible for the individual because these trips are most often a once-in-a-lifetime experience. Most river runners will not have another chance to take a better quality trip. This applies to a lesser extent to trout fishing, because most anglers visit Glen Canyon several times a year.

<u>Trout fishing.</u> At Glen Canyon, large fluctuations create very low and high water, both of which are undesirable for fishermen. Falling water can make it difficult to get downstream over rocks and sandbars

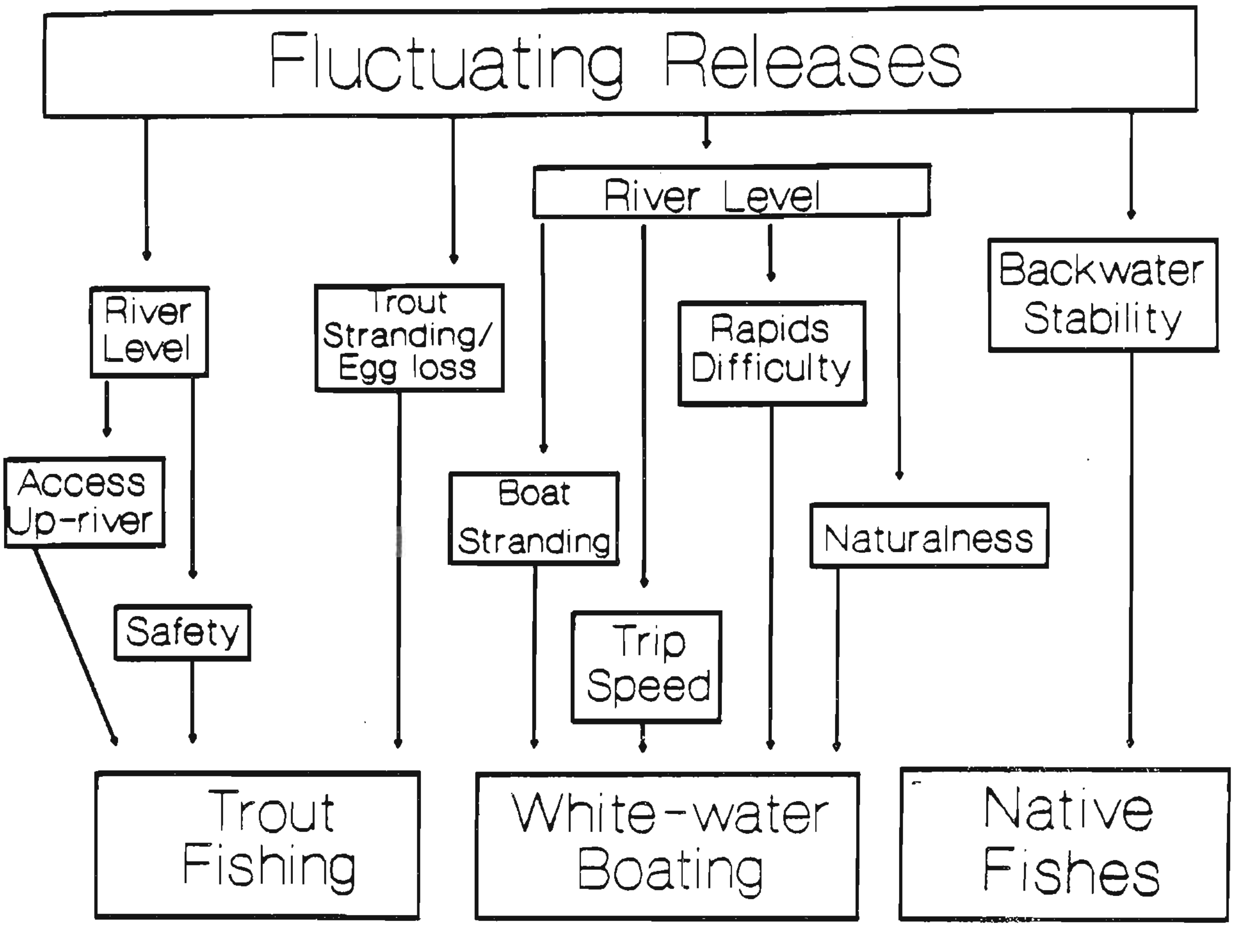


Figure VI-6. Pathways of adverse effects of fluctuating releases on critical resources.

that were submerged on the trip upriver. Although the data are not conclusive, rising water may increase the likelihood of swamping boats that are anchored in the main current or to shore. A few anglers favor fluctuating flows because they believe that rising water may stimulate feeding by fish. Nevertheless, the majority of anglers feel that the disadvantages of fluctuations outweigh the advantages. The only exception is that fluctuations are preferred to steady flows of less than 5,000 cfs. For a typical low-water year, recreation benefits from fishing are about $0.2 million higher under steady releases than under fluctuating releases. (See Appendix C, Section III.)

<u>Trout.</u> The loss of adult and juvenile fishes by stranding during fluctuating releases is well documented. Depending on the rate of flow reduction, the stranding can be substantial. Stranding is greatest from November to April when trout are spawning and reluctant to move off their spawning beds. Not only are fish stranded during fluctuating flows, but the spawning grounds are exposed, causing direct mortality to eggs and young. Because as much as 28 percent of the trout harvest may depend on natural reproduction, loss of eggs and young will reduce the trout population. However, fluctuations increase the availability of food to trout in the short-term by increasing the dislodgement and movement of algae and invertebrates. The proportion of invertebrates in trout stomachs increased during periods of fluctuating flow. But these increases were also associated with seasonal changes. (See Appendix B, Section V.) The long-term effects of fluctuations on algae and invertebrate populations are unknown.

<u>Native fish.</u> Larval common native fishes are relatively immobile, very susceptible to predation and stranding, and require quiet, warm backwaters for growth and survival. As flows fluctuate, the depth, temperature, and velocity of backwaters change, forcing fish to move into the mainstem river. This increases the risk of predation and requires an additional expenditure of energy (Appendix B, Section IV and V).

Larval humpback chub begin their life in the Little Colorado River, but rearing of many individuals occurs in backwaters of the mainstream river. High, steady mainstream flows during spring and early summer back up tributary waters at the confluence and provide favorable warm-water habitat for larval humpback chub growth. Fluctuating releases were rare during the GCES and measurement of their effects on early humpback chub life stages were not complete. In particular, measurements of the effects of fluctuating releases on juvenile humpback chub in backwaters were restricted to several days in October. At this time of year, many young-of-the-year have grown large enough to withstand cold mainstream temperatures and higher velocity currents. Little stranding of juvenile chub was observed, but indirect effects of fluctuating flows, such as reductions in food resource populations, daily displacement into cold, mainstream waters, and increased erosion of backwater sediments could not be assessed during this limited study period.

Terrestrial resources. Terrestrial resources such as beaches and vegetation are not as strongly affected by fluctuating flows as they are by floods. Because vegetation has stablized above the level of flow fluctuation, changes in flow within powerplant capacity have little effect on terrestrial vegetation, habitat, and wildlife. (See Appendix B, Section V.) However, if vegetation substrate is lost through erosion of alluvial sand deposits under fluctuating flows, terrestrial habitat will be lost in the long-term.

Sand in beaches and other deposits along the channel margins will adjust, probably within a few years, to any pattern of fluctuating flow. During adjustment, beach area is lost because of bank failure. The higher the peak flow during fluctuation, the greater the loss that occurs before the stable configuration is reached, and the smaller the stable area remaining for camping and vegetation. Loss will be greatest in narrow reaches because those reaches experience a greater change in water level for the same fluctuation range than do wide reaches. Although floods may redeposit sand at elevations above the 31,500 cfs level if sand is in sufficient supply, the new deposits are thought to be unstable. Initiation of fluctuating flows or lower steady flows after these floods will cause loss of the newly-deposited sand throughout the canyon. Loss will be greatest in narrow reaches, where competition for campsites is keenest. Redistribution of sand by fluctuating flows may reduce the area and depth of backwaters. (See Appendix A, Section II.) Sand deposited in floods of 1983-85 had not stabilized by the time measurements ended in January 1986, and it is not known whether any of these new deposits will remain once a stable condition has been reached.

IMPACT OF YEAR-ROUND FLUCTUATIONS ON RESOURCES

CRITICAL RESOURCES						
Chub	Native Fish	Trout Repro/Grow	Trout Fishing	WW Boating	Beaches	Terres. Habitat
?	–	– / +	–	–	–	–

Figure VI-7. Fluctuations have adverse impacts (-) on aquatic resources, recreation, and terrestrial resources; may benefit (+) trout growth; and have unknown (?) impacts on humpback chub.

Flood Releases Have Greatest Potential For Long-Term And Irreversible Impacts

Of the operations evaluated, flooding has the greatest potential to irreversibly impact the Colorado River in Grand Canyon. Flooding was a natural and consistent aspect of pre-dam flows. However, the large amounts of sediment carried by pre-dam flows allowed renewal of beaches and substrate for vegetation. In the post-dam period, loss of beaches, sand substrate, and marshes may be irreversible because the supply of sediment is severely reduced and is highly erratic. Floods may also irreversibly affect the vegetation by leaching nutrients from the soil (Appendix B, Section V). Nutrient-poor soil could limit productivity, change the species composition of riparian vegetation, lead to loss of wildlife habitat, and decrease the diversity and abundance of plants and animals.

Although some potential benefits of infrequent flood releases have been hypothesized, it appears that the detrimental effects of even rare flood releases (1 in 20 years) outweigh potential benefits to resources. These potential benefits are discussed below.

(1) As vegetation ages and becomes more homogeneous, the diversity of animals that depend on vegetation is often reduced. Infrequent flooding may open areas for colonization by younger individuals of the same plant species or different species, thus increasing vegetation habitat diversity, and in turn increasing animal diversity. The frequency of flooding that would enhance diversity is not known at the present time. We know from this study that diversity within the animal community along the river was increasing from 1963 to 1982, a twenty-year period of operations with almost no flood releases. We do not know how long plant and animal diversity would have continued to increase or whether the flood in 1983 will increase or decrease diversity in the long-term.

(2) If sand is in sufficient supply, floods can move sand from low elevations to high elevations where it is more useful for campsites. Redistribution of sand during floods cleans it of refuse and scours away any encroaching vegetation which may make camping more difficult. However, overall beach area will be lost during any flood, and much of the gain in sand at high elevations will be temporary.

The floods of 1983 and 1984 caused loss of area of camping beaches, especially in narrow reaches. Because this loss occurred even after the system had almost 20 years to store sand for resupply of beaches, we conclude that floods occurring more than once in 20 years will cause even greater loss of beaches unless delivery of sand from tributaries is exceptionally high.

(3) Flood flows may be required to move very coarse debris brought to the river by flows in tributaries. A large tributary debris flow, such as that which created Crystal Rapid in 1966, could make navigation very hazardous. Large annual floods of the pre-dam period adjusted these deposits, easing the constriction at rapids and making them more navigable. The size and frequency of flows needed to remove large, newly added

debris are not known. Evidence suggests that flows of 90,000-300,000 cfs may be required to maintain rapids at their pre-dam condition of navigability. These flows may very well be above the limits of releases that would ever be made as part of planned operations at Glen Canyon Dam.

We have had only a short time to monitor the response of the system to floods, and therefore have limited understanding of how the system responds to a given frequency of floods. However, based on evidence of damage from the 1983 flood, which occurred after 20 years without floods, we conclude that floods occurring more frequently than once in 20 years will result in loss of critical resources without substantial benefits.

SECTION VII: MODIFIED OPERATIONS

In this chapter we describe five ways in which the operations of Glen Canyon Dam could be modified to protect or enhance environmental and recreational resources. Each of these modified water release scenarios addresses one key environmental or recreational resource. All five scenarios eliminate flood releases and reduce or eliminate fluctuating releases, the adverse consequences of which were detailed in the previous chapter. These scenarios only approximate ideal release patterns for downstream resources. They illustrate the types of changes that could be made to protect or enhance resources, but do not include analysis of the relationship of releases to power revenues and other costs and benefits associated with operations. The alternatives are also not meant to be a representation of the complete range of operational options that would be evaluated in a NEPA compliance process.

The critical resources targeted for each scenario are:

(1) Humpback chub
(2) Common native fish
(3) Trout
(4) Beaches, terrestrial vegetation, and wildlife
(5) Fishing and white-water recreation

We combined resources that respond similarly to flows or that can be protected or enhanced within the same pattern of annual releases. Two additional modifications to current operations are addressed: (1) mimicking pre-dam releases to simulate "natural" flows, and (2) increasing the peak powerplant capacity from 31,500 cfs to 33,100 cfs.

Each scenario is represented (see Figures VII-1 to VII-6) as an annual release pattern showing monthly releases. Except where noted, the release levels shown are steady releases. In recognition of the variability of the annual runoff, each scenario has been developed in two versions: (1) a high-water year version that provides roughly 16 maf of release, and (2) a low-water year version which provides roughly 8 maf of release.

Scenarios for each resource were developed around the sensitive periods in lifestage or recreation use patterns shown in Table VI-1. The rationale for these release patterns is presented in the impacts analysis below and detailed in Appendices A-C. For each scenario, we describe the effect on the targeted resource and on the other critical resources when the scenario is compared to current operations as defined in Section VI.

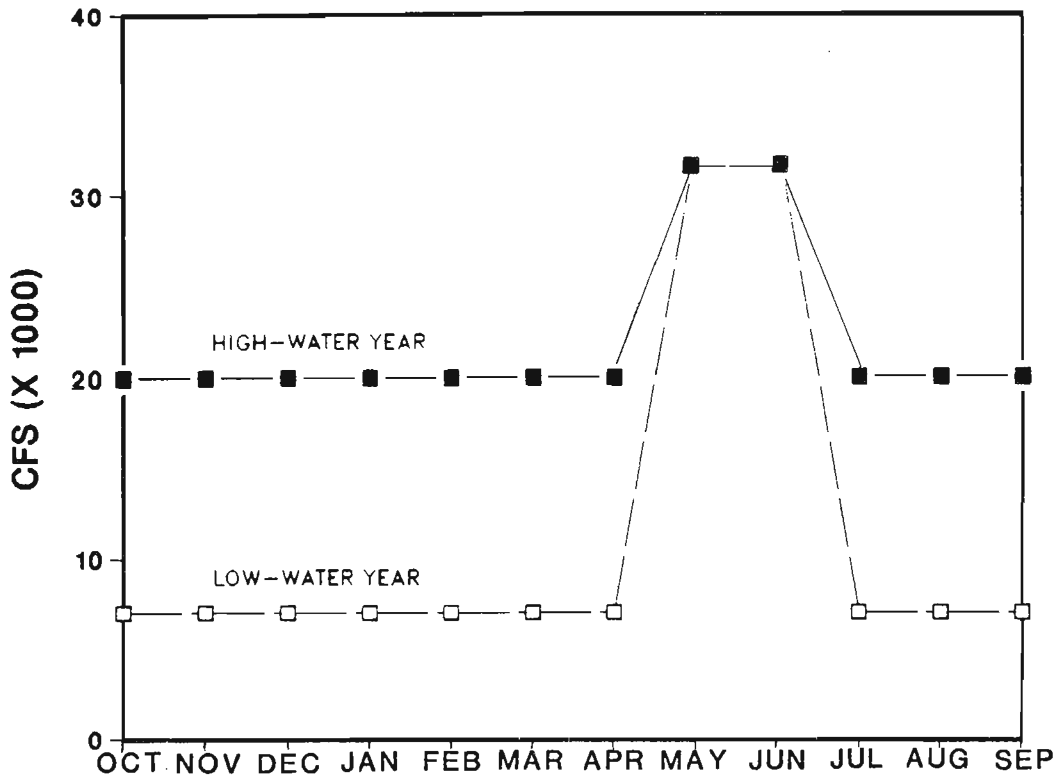
Releases For HUMPBACK CHUB Benefit Most Resources But Could Reduce Trout Growth And Beach Area

A scenario which enhances the reproduction and successful rearing of humpback chub is characterized by flows at maximum powerplant capacity in May and June, and steady flows during the remainder of the year (Figure VII-1). The high flows in May and June would back up the Little Colorado River, creating a large area of relatively warm, low-velocity flow which appears to be beneficial to humpback chub reproduction and larval survival.

When compared to current dam operations, providing releases which increase humpback chub numbers may also protect or enhance many of the other critical resources. For example, common native fish would not be subject to the daily changes in backwater location and temperature caused by fluctuating releases. Steady flows during late summer months would allow these fish to rear in a low-velocity, relatively warm environment which may enhance growth, minimize energy expenditure, and reduce predation risks. Trout reproduction and trout fishing may also benefit from this scenario compared to current operations. Although high flows during May and June reduce low-velocity habitat preferred by larval trout, spawning would be successful because spawning areas would not be exposed and adults would not be stranded by fluctuating river levels. If numbers of naturally spawned trout increased as a result, fish stocking could be decreased. However, trout growth rates could decline due to the absence of fluctuating flows, which increase short-term food availability. (See Appendix B, Section VII.)

Flow conditions for fishing and white-water boating would be improved by elimination of fluctuations. Boating safety would also improve because of the elimination of flood releases and very low flows.

RELEASES FOR HUMPBACK CHUB



IMPACT OF RELEASES FOR HUMPBACK CHUB WHEN COMPARED TO CURRENT OPERATIONS

CRITICAL RESOURCES						
Chub	Native Fish	Trout Repro/Grow	Trout Fishing	WW Boating	Beaches	Terres. Habitat
+	+	+ / −	+	+	−	+

Figure VII-1. Releases for **HUMPBACK CHUB** and impacts on critical resources.

Operations modified for humpback chub probably would be damaging to beaches in the long-term. Although floods would be eliminated, the long period of maximum powerplant flows each year would result in greater sand transport than under current operations. The resulting amount of sand stored in the main channel would be less than under current operations, making beaches more vulnerable to erosion. Also, the change each year from low to high flows would produce unstable beaches, and might result in a higher rate of erosion than under current conditions. (See Appendix A, Section V.)

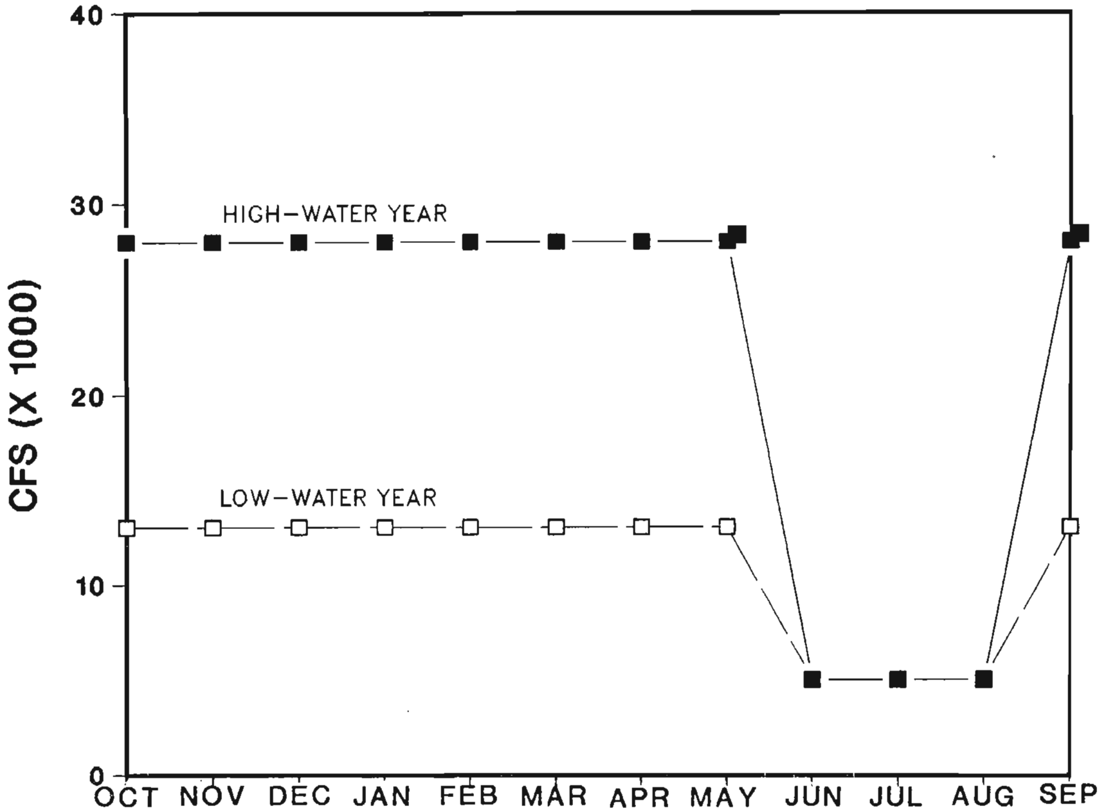
Terrestrial vegetation and wildlife both would benefit under the humpback chub scenario. The major long-term benefit to vegetation would be protection from physical removal and substrate loss similar to that which occurred following the flood releases in 1983, 1984, 1985, and 1986. However, possible long-term loss of beaches could lead to some loss of vegetation and wildlife populations.

Releases For COMMON NATIVE FISH Have Strong Negative Effects On White-Water Boating

The common native fish scenario (Figure VII-2) is based on the evidence that the largest number of backwaters are available at relatively low flows (5,000 cfs). Therefore, low flows from June to August would increase the availability of backwater habitats during the vulnerable rearing period over those available under current operations. The remaining water is evenly distributed from September through May. Preliminary research has shown that flows of 5,000 cfs can triple the number of available backwaters compared to flows of 28,000 cfs (Appendix B, Section V). However, it is possible that a similar number of backwaters would be available under flows higher than 5,000 cfs. Additional surveys of backwater numbers at different flow levels are needed to refine this scenario.

The number of backwaters is increased if low flows are preceded by steady flows because sandbars deposited in eddies show more topographic relief under these conditions, and more backwaters form when flows are dropped (Appendix A, Section II). Fluctuations continually change the depth, temperature, and velocity

RELEASES FOR COMMON NATIVE FISH



IMPACT OF RELEASES FOR COMMON NATIVE FISH WHEN COMPARED TO CURRENT OPERATIONS

CRITICAL RESOURCES						
Chub	Native Fish	Trout Repro/Grow	Trout Fishing	W W Boating	Beaches	Terres. Habitat
?	+	+ / –	+	–	+	+

Figure VII-2. Releases for **COMMON NATIVE FISH** and impacts on critical resources.

of backwaters, forcing larval fish to either move into the mainstem river or be stranded and die.

The common native fish scenario may have a negative impact on humpback chub in June, when humpback chub larvae are still dependent on rearing habitat in the Little Colorado River. Low flows during this period would allow the Little Colorado River to flow freely into the mainstem, thus transporting larval humpback chub into the Colorado, an inhospitable environment. By July, many larval humpback chub have grown to a size where they can survive in the mainstem and low flows may no longer affect them.

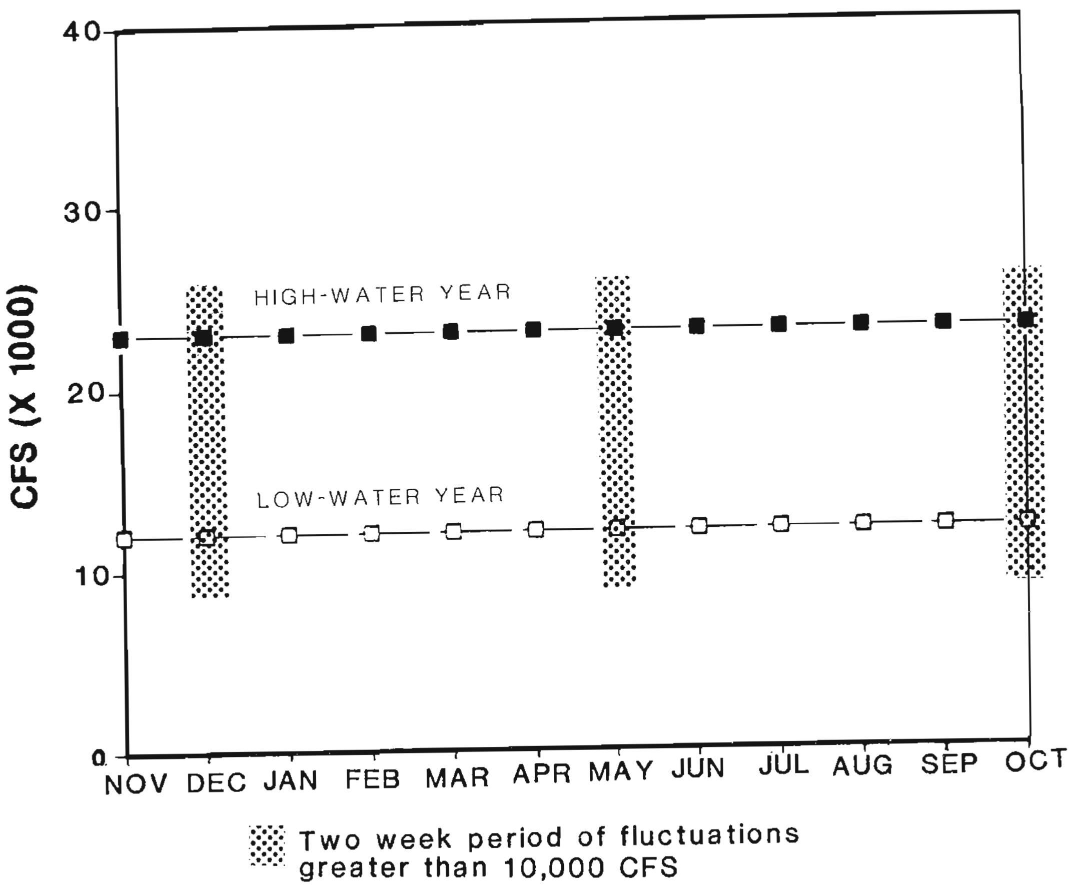
Steady flows in winter would benefit trout by eliminating the low water that accompanies winter fluctuations and exposes spawning areas. However, absence of fluctuations would decrease food availability. Sustained low flows in the summer would reduce habitat and food availability for trout. Beaches, terrestrial vegetation, and most wildlife would benefit from this nearly steady-state scenario compared to current operations (Appendix A, Section II). Vegetation would benefit from the lack of floods and expand in area down to the level of the 26,000 cfs peak flow. However, low flows in summer may cause moisture stress to young plants.

White-water boating would be seriously impacted under this scenario. Low flows during the peak rafting months of June, July, and August would severely reduce the recreational value of white-water boating and increase hazardous conditions in the rapids. The negative impact to white-water recreation during these three months generally outweighs the potential benefits to rafting during the remainder of the year. When compared to current operations, an average of $1.5 million in white-water recreation benefits would be lost annually through releases for common native fish. (See Appendix III, Chapter IV.)

Releases For TROUT Balance Conflicting Requirements For Reproduction And Growth

The seasonal needs of rainbow trout reproduction and growth within the Glen Canyon fishery suggest that both

RELEASES FOR TROUT



IMPACT OF RELEASES FOR TROUT WHEN COMPARED TO CURRENT OPERATIONS

CRITICAL RESOURCES						
Chub	Native Fish	Trout Repro/Grow	Trout Fishing	WW Boating	Beaches	Terres. Habitat
?	+	+ / ?	+	+	+	+

Figure VII-3. Releases for **TROUT** and impacts on critical resources.

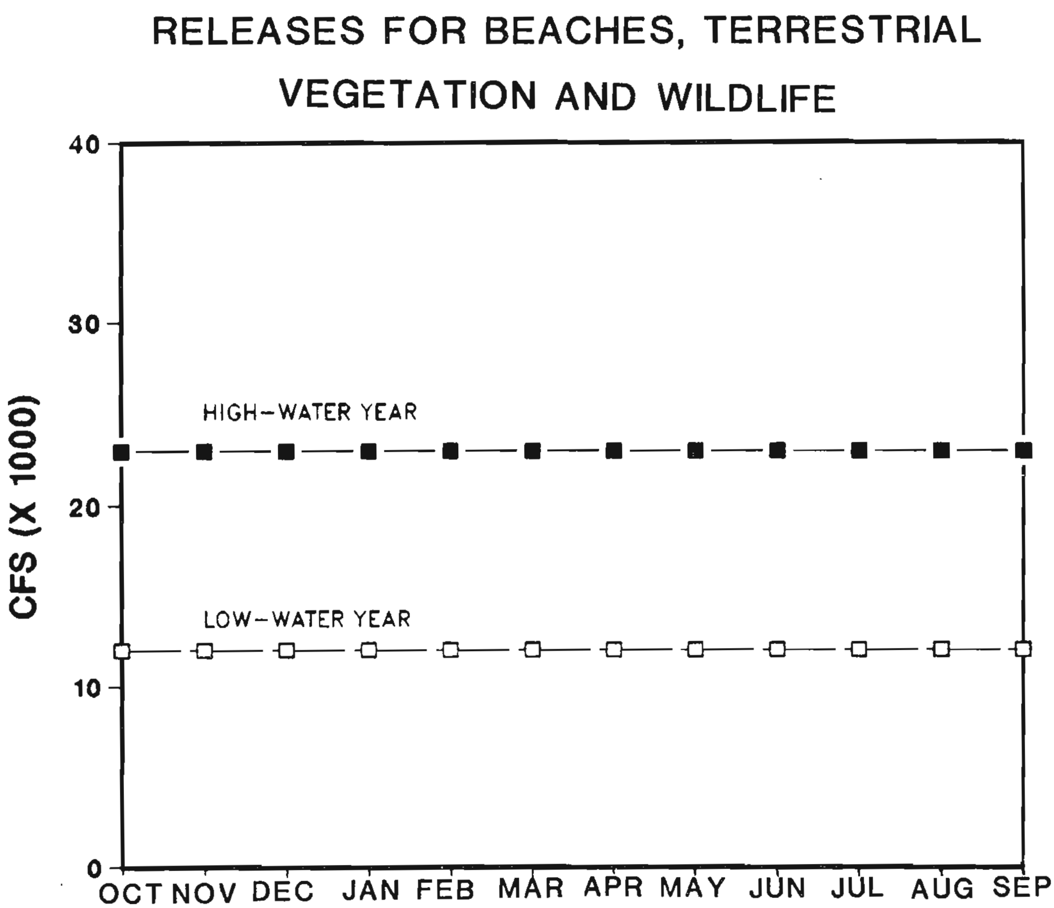
fluctuating and steady flows may be beneficial at specific times of the year (Figure VII-3). Steady flows from December through March that provide minimum flow of 8,000 cfs would protect trout spawning areas from dewatering. Fluctuations which strand adults and eggs would be eliminated, providing increased protection for natural reproduction. Once fry have emerged from spawning areas in March, a minimum flow would not be needed. Trout fry would benefit from keeping flows under 25,000 cfs to maintain nearshore, low-velocity rearing habitat.

Three two-week periods of fluctuations were added to this otherwise steady flow scenario to benefit trout growth by increasing the available food supply. It is not known whether these three two-week periods of fluctuations are adequate to increase trout growth, or if they would be as beneficial to trout growth as the nearly year-round fluctuations of current operations. In addition, the effects of fluctuations on the long-term maintenance of invertebrate populations is not completely understood. (See Appendix B, Section V.)

The impact of the trout scenario on other critical resources would be mostly beneficial. The reduction in fluctuations and elimination of flood releases would improve conditions for trout fishing and white-water boating, and reduce loss of beach area, terrestrial habitat, and wildlife. The impact of the trout scenario on humpback chub is unknown because it is not known whether the high flows in May and June are high enough to back up the Little Colorado River and increase nursery habitat for larval chub. Backwaters would remain more stable under this plan compared to current operations, thereby benefiting common native fish.

Releases For BEACHES, TERRESTRIAL VEGETATION, AND WILDLIFE Are Mostly Favorable To Other Resources

Protection of terrestrial habitat and beaches requires a scenario (Figure VII-4) that eliminates both frequent flooding and extreme fluctuations. The elimination of floods would protect camping beaches from loss. Steady flows would be lower than the peaks of current fluctuations, even in high-water years. Stabilization of



RELEASES FOR BEACHES/TERRESTRIAL VEGETATION/WILDLIFE WHEN COMPARED TO CURRENT OPERATIONS

CRITICAL RESOURCES						
Chub	Native Fish	Trout Repro/Grow	Trout Fishing	W W Boating	Beaches	Terres. Habitat
?	+	+ / −	+	+	+	+

Figure VII-4. Releases for **BEACHES, TERRESTRIAL VEGETATION, AND WILDLIFE** and impacts on critical resources.

camping beaches and substrate to this lower peak flow level would result in more area of beaches and vegetation than under current operations (Appendix A, Section V).

The number of backwaters available to larval native fish would be greater under this scenario compared to current operations because peak flows would be lower in both low- and high-water years. In addition, the quality and stability of backwaters would increase due to elimination of fluctuations.

The impacts on humpback chub of steady flows of 23,000 cfs in high-water years and 12,000 cfs in low-water years is uncertain, because these flows may not be high enough to back up the mouth of the Little Colorado River.

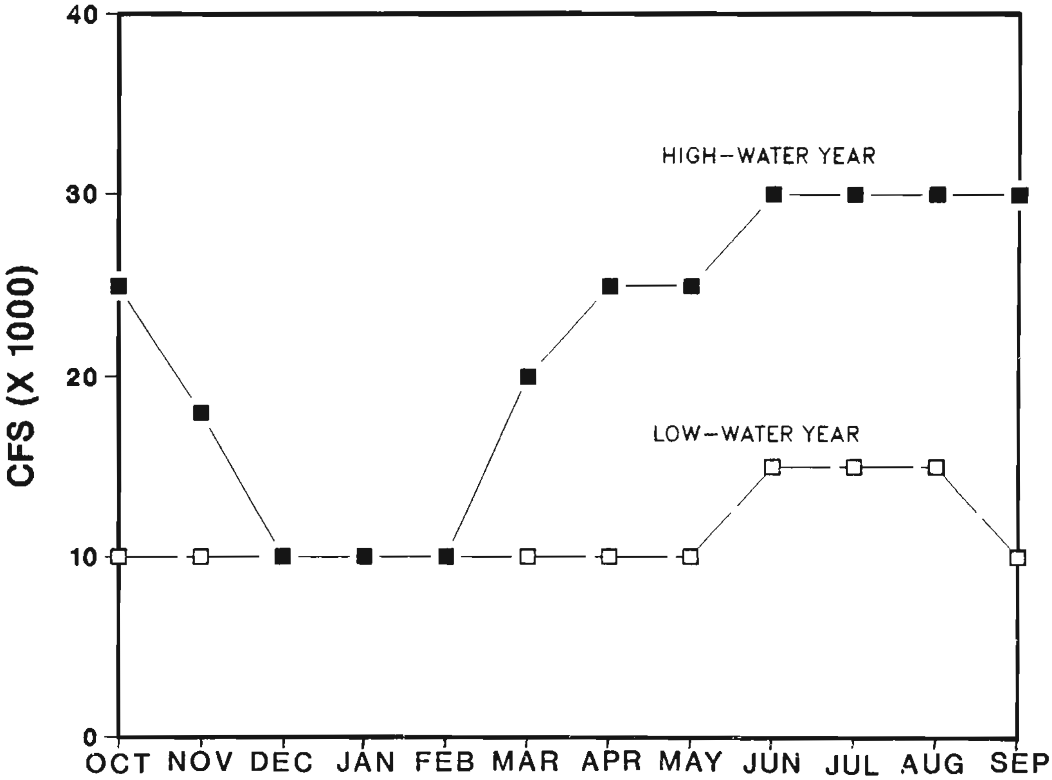
White-water boating would be enhanced by the elimination of fluctuating releases. The recreational value of the fishery and boating safety would also increase under the more moderate flows of this scenario (Appendix C, Section III).

Releases For FISHING AND WHITE-WATER RECREATION Are Mostly Favorable To Other Resources

This scenario (Figure VII-5) is designed to provide desirable conditions for anglers during the winter and for boaters during the primary white-water season. Eliminating fluctuations would increase recreation benefits for anglers and particularly for white-water boaters. However, the two groups prefer quite different flow levels. Anglers prefer approximately 10,000 cfs and white-water boaters prefer flows near 30,000 cfs. The conflict between these groups is reduced by the fact that fishing-use peaks in winter, whereas 92 percent of white-water boating occurs from May to October.

No negative effects of this scenario to the other critical resources have been identified. However, the effect upon humpback chub is unknown for the reasons described in the section above. Common native fish would benefit from this scenario during low-water years due to decreased peak flows and lack of fluctuations.

RELEASES FOR COMBINED RECREATION



IMPACT OF RELEASES FOR COMBINED RECREATION WHEN COMPARED TO CURRENT OPERATIONS

CRITICAL RESOURCES						
Chub	Native Fish	Trout Repro/Grow	Trout Fishing	W W Boating	Beaches	Terres. Habitat
?	+	+ / –	+	+	+	+

Figure VII-5. Releases for **COMBINED RECREATION** and impacts on critical resources.

However, in high-water years, it is likely that backwaters would be fewer under this scenario, than under current operations, because water would be rising rather than dropping prior to larval rearing from June to August.

Releases To Mimic "NATURAL" CONDITIONS Have Strong Negative Impacts On Several Resources

It has been suggested that dam operations which mimic pre-dam flows (i.e., outflow equal to inflow) would lead to more natural conditions downstream. Such a release scenario is not possible under existing constraints. However, for the purposes of evaluating the impact of such flows, we have ignored these constraints and assumed that the releases could be made in a pattern similar to that in Figure IV-1. It must be noted, however, that such releases would still be much colder and contain much less sediment (Figure IV-2) than pre-dam river flows.

Humpback chub would probably fare well with a more "natural" release pattern because flood flows increase the area of reproductive and rearing habitat at the mouth of the Little Colorado River (Figure VII-6). Because flows of this scenario would be colder than pre-dam flows, common native fish, which before the dam used the main channel for larval rearing, would still be dependent on backwaters for rearing. Low flows and associated backwaters would be available in the largest numbers in August, September, and October, a period very late for larval rearing of common native fish. Therefore, although flow volume and timing would be similar to the pre-dam river, the cold water would prevent chub or common native fish from expanding their spawning beyond areas currently used.

The trout fishery and fishing would be severely degraded under these conditions. Low flows (3,000-8,000 cfs) would be common through most of the winter and early spring when fishing use is heaviest. The periods of very low water would create relatively undesirable fishing conditions because of reduced access upriver and damage to boats. These low flows would also reduce trout spawning and rearing.

IMPACT OF RELEASES TO MIMIC "NATURAL" CONDITIONS WHEN COMPARED TO CURRENT OPERATIONS

CRITICAL RESOURCES						
Chub	Native Fish	Trout Repro/Grow	Trout Fishing	WW Boating	Beaches	Terres. Habitat
?	—	— / —	—	—	—	—

Figure VII-6. Releases to mimic **"NATURAL" CONDITIONS** adversely affect most critical resources.

Frequent large floods combined with the reduced supply of sediment will greatly reduce streamside terrestrial habitat and camping beaches. Flood flows would remove the existing vegetation in a zone between the 31,500 cfs and 100,000 cfs flow levels and greatly reduce the area of substrate and beaches for vegetation. The GCES have shown that tributary supply of sediments would not be sufficient to replenish campsite beaches following repeated clear-water flooding. Terrestrial wildlife would decrease in both numbers and diversity as the habitat upon which they depend was eliminated. (See Appendix A, Section V.)

The use period for white-water boating would be reduced because boaters would have to avoid the extremely low and high flows which present multiple hazards to both boaters and equipment. Further, the quality of the experience would be dramatically reduced following loss of beaches, vegetation, and wildlife along the river corridor. In conclusion, "natural" conditions cannot be recreated without reestablishing warm river temperatures and a large, consistent supply of sediment.

The Modified Release Patterns, Except For The Releases To Mimic Pre-Dam Flows, Are Generally Beneficial To Downstream Resources

Figure VII-7 shows the impacts of the modified release scenarios for all critical resources combined on one matrix. The resources targeted by the scenarios are shown at the left of each row of the matrix. This matrix can be scanned vertically to see how each resource fares under the various scenarios. For example, the four question marks for humpback chub reflect the uncertainty about the flows needed to increase rearing habitat in the Little Colorado River. The pluses for trout fishing reflect the improved fishing conditions that would result from all scenarios because they all involve dramatic reductions in the frequency of very low, very high, and fluctuating releases. The pluses for vegetation and wildlife reflect benefits of removing floods, whereas those for common native fish reflect the improved quality and stability of backwaters when fluctuating flows are eliminated.

The minuses in the matrix highlight areas where efforts to improve one resource would likely harm another. The major conflict occurs under the humpback chub scenario between high water to increase humpback chub populations in the summer and loss of sand because of increased sediment transport by higher flows.

Impacts Of INCREASING POWERPLANT CAPACITY From 31,500 cfs To 33,100 cfs Cannot Be Fully Assessed Due To Limited Information On How Operations Will Change

The Uprate and Rewind Program was completed in April 1987. The changes in dam operations due to this program have not yet been fully specified by BOR. It is not possible at this time to specify precisely how the new powerplant capacity will affect future dam operations. Variability in forecasts, management options, and physical system limitations will impact the actual releases scheduled. The way that the new

RESOURCE IMPACTS MATRIX

MODIFIED OPERATING PLANS	CRITICAL RESOURCES						
	Chub	Native Fish	Trout Repro/Grow	Trout Fishing	WW Boating	Beaches	Terres. Habitat
Chub Plan	+	+	+ / −	+	+	−	+
Common Native Fish Plan	?	+	+ / −	+	−	+	+
Trout Plan	?	+	+ / ?	+	+	+	+
Beaches/ Habitat/ Wildlife Plan	?	+	+ / −	+	+	+	+
Combined Recreation Plan	?	+	+ / −	+	+	+	+

Figure VII-7. The conflicts among resources are between releases for Humpback Chub vs. Trout Growth and Beaches, and between releases for Common Native Fish vs. Trout Growth and White-Water Boating.

capacity will be used has not been formalized and until it is, impacts cannot be assessed.

Use of the uprated capacity in the Glen Canyon generators may lead to several changes in flow patterns from the dam. These changes would be most apparent in water years with moderate runoff, which occur approximately 30 percent of the time. In these years, the peak releases may be raised from 31,500 cfs to 33,100 cfs. This corresponds to a maximum rise in river level of less than one foot. During periods of fluctuation, the peak flows may also be increased to 33,100 cfs. This would require either lowering the bottom end of fluctuations by approximately 2,000 cfs or by increasing the rate of rise and fall in the pattern of releases. In years of high runoff, which also occur approximately 30 percent of the time, the effect of the uprate would be primarily to raise the steady releases during the spring runoff months from 31,500 cfs to 33,100 cfs (Appendix D, Section II).

Changes in the level of steady releases from 31,500 to 33,100 cfs are not likely to affect recreation significantly. However, increases in the range or the rate of fluctuations would have a negative effect on both fishing and white-water boating.

For some resources, the actual impact of the Uprate and Rewind Program may be more than the change from 31,500 to 33,100 cfs. Before this program was completed, discharges between 27,500 and 31,500 cfs were infrequent due to reservoir elevation and equipment limitations. Sand-dependent resources and vegetation therefore may have stabilized in many areas to a level corresponding to a discharge closer to 27,500 than to 31,500 cfs. The difference in water level between 27,500 and 33,100 cfs is between 1.0 and 1.5 feet depending upon the width of the reach.

A change in water level of this size could result in significant loss of camping beach area, substrate, backwaters, and areal extent of vegetation, particularly in narrow reaches. No species of terrestrial vegetation or wildlife would likely be lost from the canyon, but the number of nesting birds and other wildlife could decline.

An increase in amplitude or rate of change of fluctuations could increase the numbers of stranded fish and loss of backwaters. Increase in the frequency of low flows could increase reproductive losses for trout.

Non-Operational Approaches May Also Protect Or Enhance Downstream Resources

Several non-operational alternatives could offset impacts to downstream resources. Although these alternatives have not been systematically evaluated, positive and negative aspects are described where known.

Trout reproduction. The need for minimum releases during the winter to protect trout spawning beds and to reduce stranding of adult fishes can be relaxed by increased stocking with hatchery fish. Increasing the stock of fingerling trout could minimize the impact of losses in the natural population under fluctuating flows. Supplemental stocking in the Lees Ferry reach might eliminate the apparent conflict between the fluctuating flows required for trout growth and the steady flows needed to protect natural reproduction. However, stocking probably would not replace reproductive losses for fish downstream. The number of fish required for stocking and the cost of such a program have not been determined. Further, the loss of naturally produced rainbow trout may adversely affect the quality of the fishing experience for some anglers who prefer to catch "wild" fish (Appendix C, Section IV).

Humpback chub and common native fishes. If water temperature in the mainstem were increased to 62 degrees F during May and June, humpback chub might expand their spawning area into the mainstem Colorado River, reducing their dependence on a relatively small area of habitat in the Little Colorado River. In addition, increased water temperature could allow reintroduction of endangered fish species, such as the Colorado squawfish, that were lost to the river after construction of the dam.

Some warming of tailwater releases through the summer period would also enhance growth of native fishes and trout. In addition, increased water temperature would increase the availability of low-velocity, warm-water habitats required for rearing of larval common native fishes and possibly reduce their current dependence on backwaters. The only practical way to increase temperatures over several months, given the changing elevations of Lake Powell, is to modify the dam intake structure to allow intake of warmer water nearer the surface of the reservoir.

Possible adverse consequences of such a modification would have to be evaluated prior to implementation. These include the cost of dam modification, the effect of temperature increase on the trout fishery, the change in water quality of both Lake Powell and Lake Mead, and the potential for increase in warm-water exotic species that could prey on or compete with hump-back chub or other native fishes.

Marshes. The high floods in 1983 eliminated 95 percent of the marshes along the river. These specialized habitats which were rare or absent before the construction of Glen Canyon Dam, are important in maintaining high vertebrate diversity. If they do not recover naturally, structural measures could be used to artifically recreate the marshes that were present between 1963 and 1983. Since little is known about marsh formation or ecology in Grand Canyon, research would need to be conducted prior to considering any structural features.

White-water boating. Fluctuating releases have many negative effects on white-water boating, such as the need for moving boats at night, waiting for better flows, the unnaturalness of fluctuations, and the difficulty of selecting campsites and mooring locations. Mitigating these impacts of fluctuations through non-operational means would be very difficult. The only non-operational method we are aware of is construction of a re-regulating dam downstream of Glen Canyon Dam to catch and dampen the fluctuating releases. Such structures have been proposed in the past and rejected because of their unacceptable impact on Grand Canyon National Park.

The difficulty of navigating rapids at high flows could be mitigated by using larger boats, but this would exacerbate problems with rapids at low flows. Also, it is unlikely that river runners would willingly change the type of boat they use. For example, it would be difficult for private boaters to obtain and use larger boats (motor or oar-powered), and the use of motors would be resisted by most private boaters.

The primary hazard associated with white-water boating is drowning. The water released from the dam is extremely cold and quickly renders individuals helpless. Since 1980, five individuals have died from drowning in white water, some after relatively short periods in the water. Warming the releases to near 60 degrees F during the boating season would significantly reduce the threat of hypothermia-related drowning.

A consistent finding from surveys and discussions with white-water boaters and anglers is that the adverse effects of undesirable dam releases can be reduced by early, reliable communication of the planned dam release schedule to the river users. This helps anglers and particularly white-water boaters to plan their trip itineraries to reduce problems with flows.

Camping beaches. Artificial protection of camping beaches by construction of protective revetments (concrete or stone riverbank facings) or jetties at critical locations, or resupply of sand into the river are actions which could be undertaken to protect or rebuild sand deposits. The acceptability, feasibility, and possible impacts of such measures have not been evaluated.

SECTION VIII: CONCLUSIONS AND MANAGEMENT OPTIONS

Conclusions

■ **Flood releases and fluctuating releases from Glen Canyon Dam have a significant effect on many of the downstream environmental and recreational resources.**

Adverse downstream consequences are caused primarily by sustained flood releases significantly greater than powerplant capacity and by fluctuating releases. The most important impacts identified are the erosive effect of floods on sand deposits and vegetation and the impact of fluctuations on white-water recreation and aquatic resources.

Continued flood releases will substantially reduce sand deposits in Grand Canyon, which are essential to vegetation and wildlife and are highly valued by white-water boaters. Replenishment of sand in beaches is now dependent on sand delivered by tributaries within Grand Canyon. Because the amount of sand for resupply is much less than before dam construction and is highly variable from year to year, these erosive effects are probably permanent. For white-water recreation alone, loss of a substantial number of beaches could reduce recreation benefits by $5.2 million per year. Flood releases also double the risk of white-water boating accidents at major rapids, compared to flows below powerplant capacity. Even infrequent floods cause loss of camping beaches and vegetation substrate, and it appears that this loss is irreversible. Even though infrequent flooding may benefit some resources, the magnitude, duration, and frequency needed to provide those benefits are unknown. Loss of resources could be prevented by avoiding floods until the response of resources to floods is better understood.

Spring flood releases have no apparent long-term negative impact on humpback chub, common native fish, or trout. In fact, these high flows may actually benefit humpback chub.

Daily fluctuations substantially reduce the value of white-water recreation and trout fishing by degrading the natural character of the environment and making the management of white-water and fishing trips more difficult. In a typical year, elimination of fluctuations can increase recreation benefits by $0.8 million.

Fluctuations lead to a loss of backwater habitat for common native fish and may reduce natural trout reproduction, although fluctuations increase food availability for these fish over the short-term.

Although fluctuations do not appear to have a long-term, continuous impact on beaches, vegetation, or wildlife, the area available for camping and establishment of vegetation would be less under fluctuating flows than under steady flows of the same volume.

- **It is possible, within the Operating Criteria, to operate during low- and high-water years in ways to prevent future degradation and in some cases enhance downstream resources.**

Impacts to most critical resources can be reduced by reducing fluctuations, raising minimum flows, and eliminating flood releases to the extent possible. The closer the operation of the dam comes to steady release of the annual runoff each year, the less degradation occurs to environmental resources. Trout may be an exception, because fluctuations apparently increase their short-term food availability.

- **The effects of the Uprate and Rewind Program on downstream resources cannot be determined at this time.**

The changes in dam operations due to the Uprate and Rewind Program are not yet determined. It is not possible at this time to specify precisely how the new powerplant capacity and subsequent management will affect future dam operations.

- **Reducing the vulnerability of the endangered humpback chub to catastrophies in the Little Colorado River watershed must depend on non-operation alternatives.**

Warming the temperature of the mainstem river could create habitats for chub breeding in other locations, but such efforts must first reconcile the possibility of increasing populations of potential competitors and predators of humpback chub. In addition, the vulnerability of the humpback chub population might be reduced through efforts to protect the Little Colorado

River watershed and critical habitat from environmental threats.

■ **Several additional non-operational or management alternatives exist which could protect or enhance the environmental resources downstream of Glen Canyon Dam.**

Implementation of these alternatives might relax some constraints on operations that would be necessary to prevent resource degradation.

Management Options

This study was designed to provide information for a decision by the Secretary of the Interior concerning the need to take further action to reduce impacts to the environment and recreation in Glen and Grand Canyons. Based on the study finding that the current operations of Glen Canyon Dam adversely affect the downstream environmental and recreational resources, the study team has identified some possible management options.

■ **Feasibility studies of changes in operations:**

These studies would evaluate the economic, social, legal, environmental, and physical consequences of operational modifications to protect downstream environmental and recreational resources. National Environmental Policy Act activities would be included.

As part of this effort, policy questions might also be addressed as one means of reducing the probability of flood releases.

■ **Feasibility studies of non-operational means to protect critical resources:**

Non-operational means may be available to protect resources without constraining dam operations. Possible measures include hatcheries to replace trout reproductive losses and a multi-level dam intake structure to warm water to recover humpback chub and common native fishes. These and other non-operational measures should be investigated further since they were not evaluated as part of this study. Many unresolved questions remain concerning the effects of dam operations, particularly low and fluctuating flows, on critical resources, especially humpback chub. Studies designed to answer these questions will require the provision of sufficient and timely periods of low and fluctuating flows.

■ **Continued research and monitoring of critical resources:**

The need exists for additional research to fill gaps in current knowledge of resources and how they are affected by flows. Closely allied with this is the need for monitoring downstream resources to confirm current predictions about the impact of dam operations, to provide early warning of any deteriorating conditions, and to identify long-term resource changes not recognizable in a short-term study. Monitoring activities could be integrated into National Park Service resource management and monitoring plans and similar programs conducted by other agencies. (Monitoring and research needs are given in the attached appendices.)

■ **A mechanism for coordinated inter-agency management of Glen and Grand Canyons. This could include:**

Development of a long-term management plan that explicitly establishes goals and priorities for the protection of critical resources.

Development of a plan for continued monitoring and research in Glen and Grand Canyons.

Formation of a management group which would implement and oversee the monitoring and research plan.

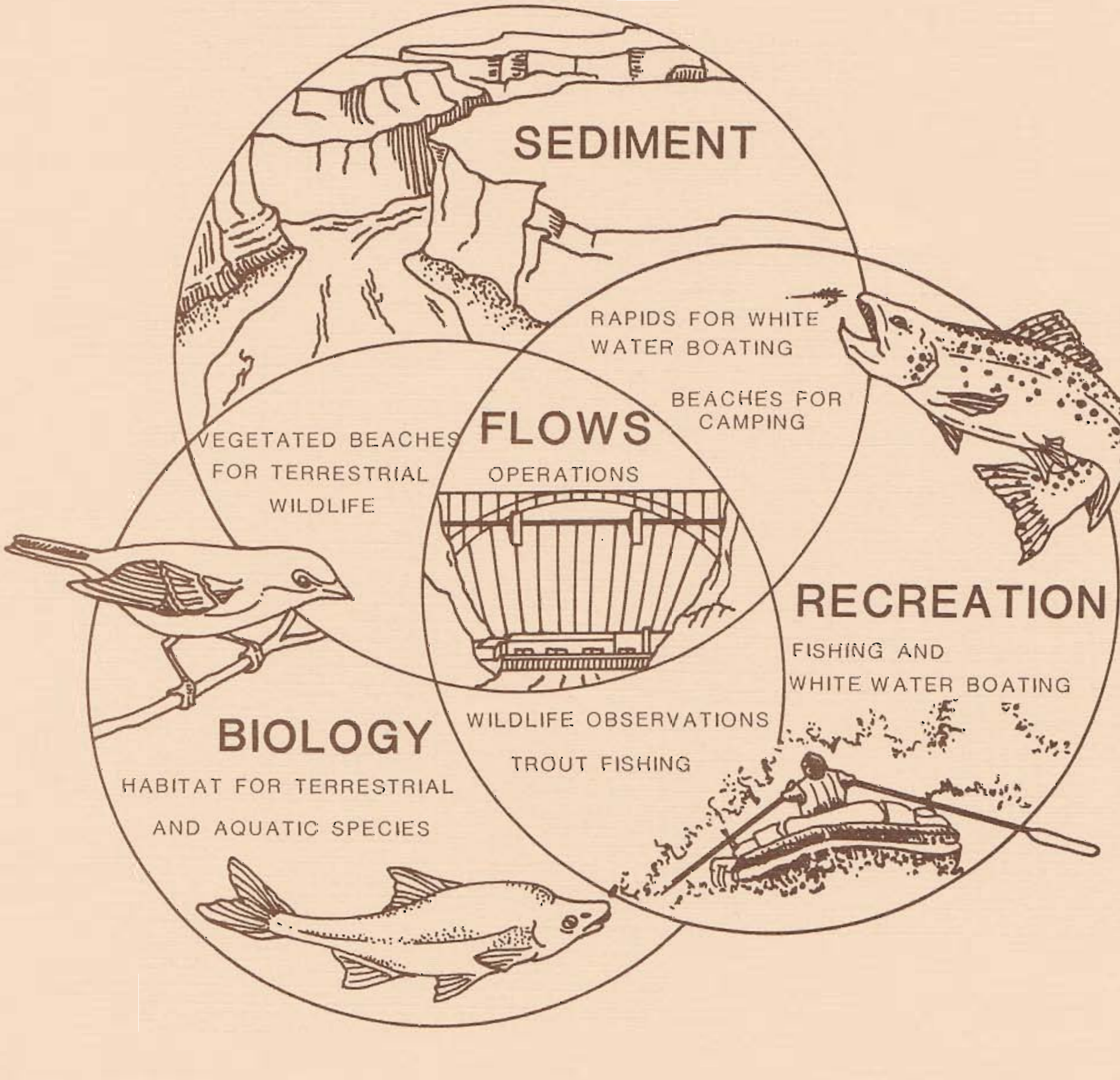
APPENDICES

A. SEDIMENT REPORT

B. BIOLOGY REPORT

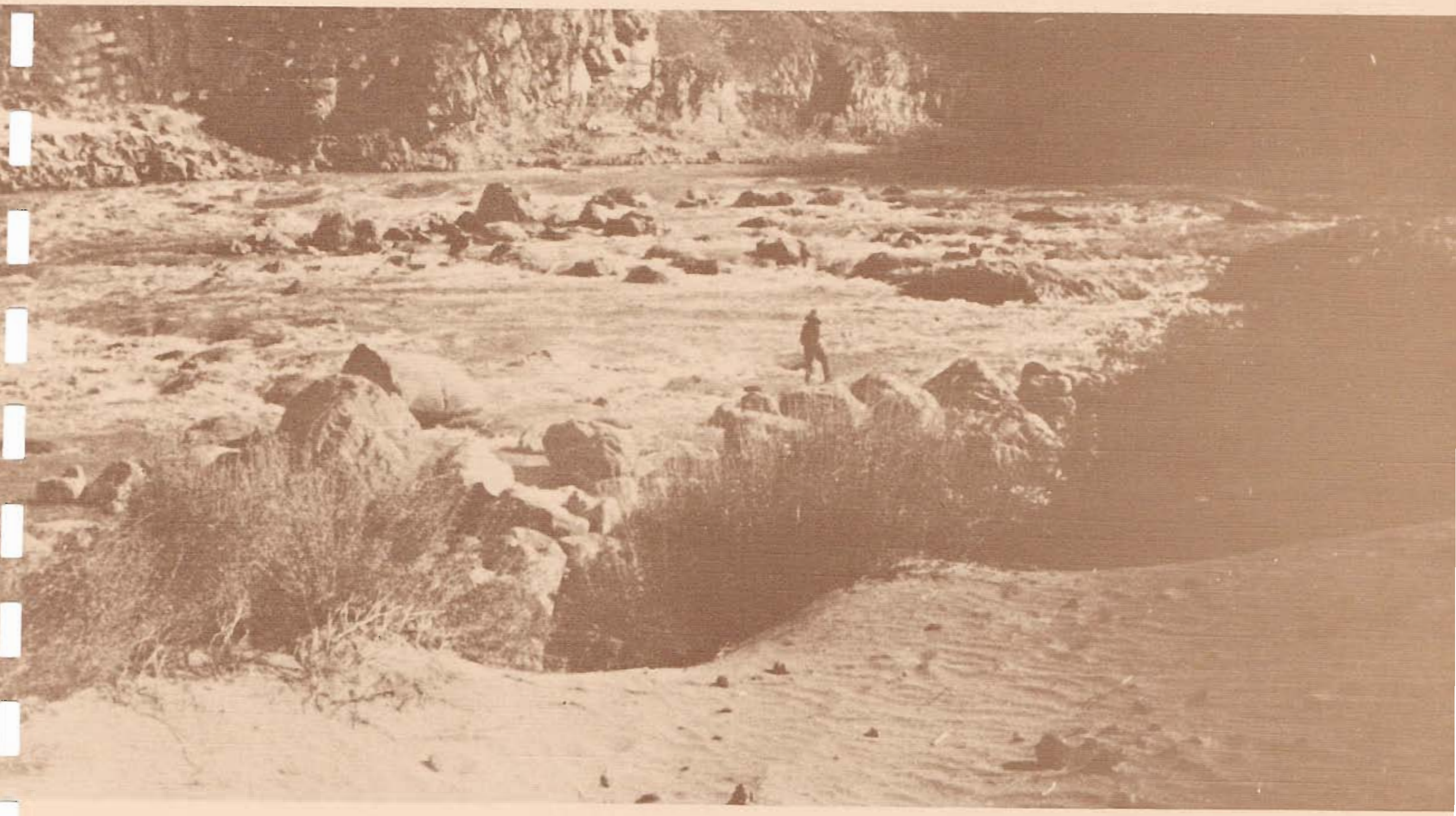
C. RECREATION REPORT

D. OPERATIONS REPORT



SEDIMENT REPORT

Appendix A



HANCE RAPID
1911 KOLB

Hance Rapid at Red Canyon, Colorado River Mile 77.5, circa 1911. Photo courtesy of the Emery Kolb Collection, Northern Arizona University, Flagstaff, Arizona.

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SECTION I: INTRODUCTION AND MAJOR FINDINGS

Sediment is literally the foundation of the riparian environment and recreation along the Colorado River in Grand Canyon National Park (**Grand Canyon**) (Figure A-1). Deposits of sand are substrate for the terrestrial biological resources and are used by boaters as campsites, lunch stops, and attraction sites. Deposits of boulders form rapids, a highlight of river recreation in Grand Canyon. Gravel bars are used by some fish species for spawning.

Before initiation of the Glen Canyon Environmental Studies (GCES), several researchers, such as Laursen, Ince, and Pollack (1976) and Howard and Dolan (1981), had studied sediment transport and sand deposits in Grand Canyon. The results of these previous studies initially predicted that sand deposits would eventually be depleted after completion of Glen Canyon Dam, but later studies indicated that large scale erosion of sand deposits had ceased by the late 1970s (Howard and Dolan 1981). Concern over the effect on camping beaches of more recent flood releases, and the potential change in operations of Glen Canyon Dam made possible by improvement (Uprate and Rewind Program) of the generators, required the undertaking of new studies.

Sediment-Dependent Resources

Sediment resources identified by researchers and management agencies as those most important to biological resources and to recreation were camping beaches, sand which is substrate for vegetation, backwaters in sand deposits which are used by juvenile fish, and rapids. Although sand stored in main channel pools is not in itself important to the biological system or recreation, it is considered as a resource in this study because of its potential indirect importance to other resources.

Some narrow sand deposits which typically continuously line the channel margin in wide reaches of Grand Canyon, or discontinuously line the channel margin in narrow reaches, are overgrown by vegetation and used by wildlife. These deposits are called **channel margin deposits** (Figure A-2). However, the largest and most numerous sand deposits are located near debris fans which form at the mouths of tributaries. At these debris fans, the channel is typically narrower and shallower than elsewhere, and large zones of

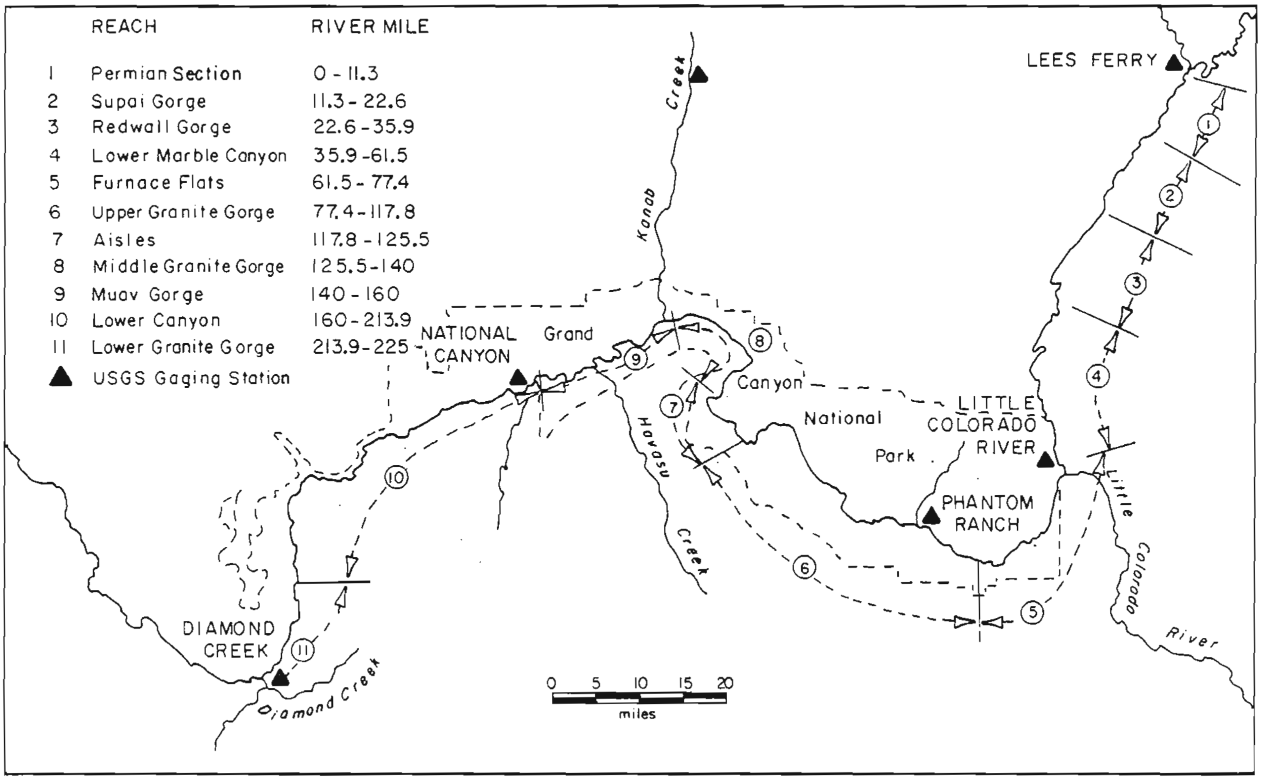


Figure A-1. Reaches within the study area. (After Schmidt and Graf 1987, Figure 4)

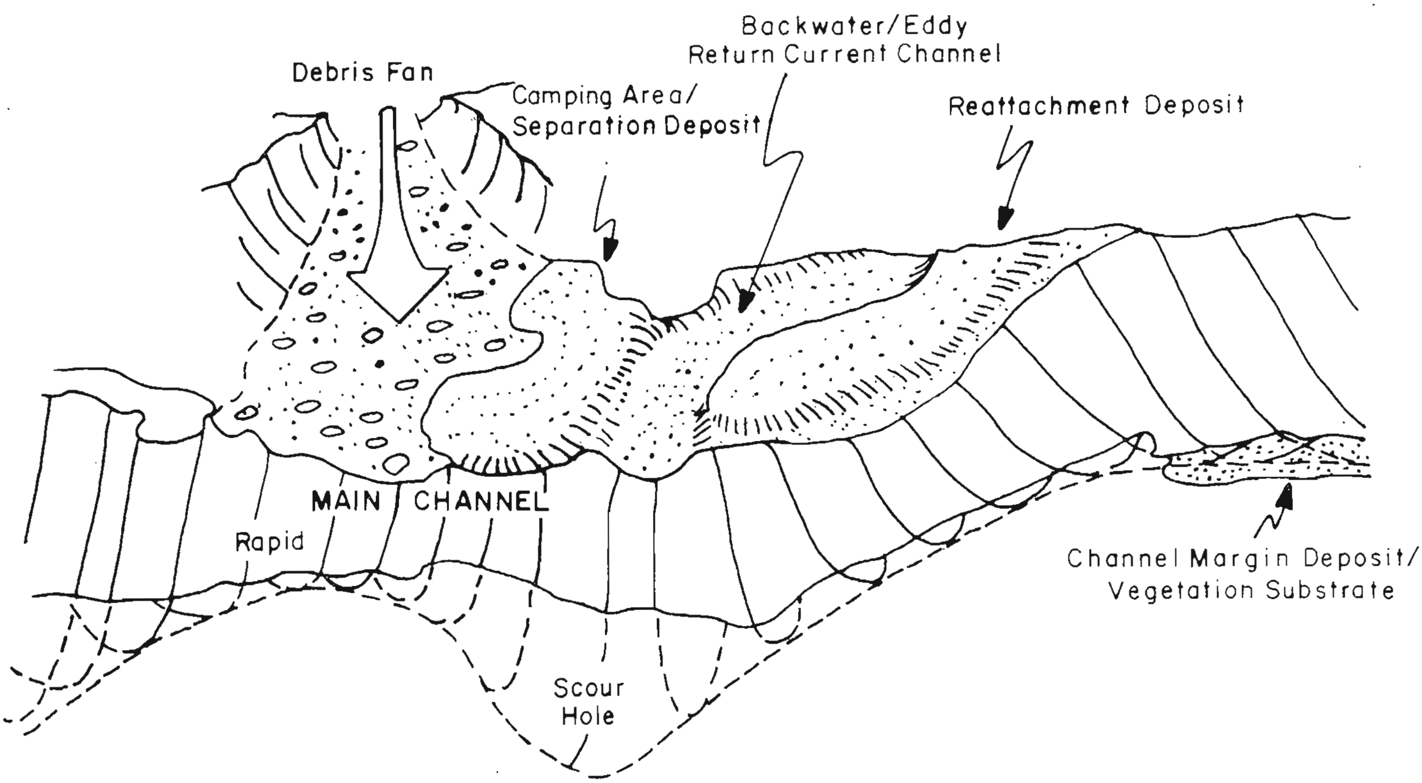


Figure A-2. Sand deposits and sediment-dependent resources in the vicinity of a typical recirculation zone. (After Schmidt and Graf 1987, Figure 3B)

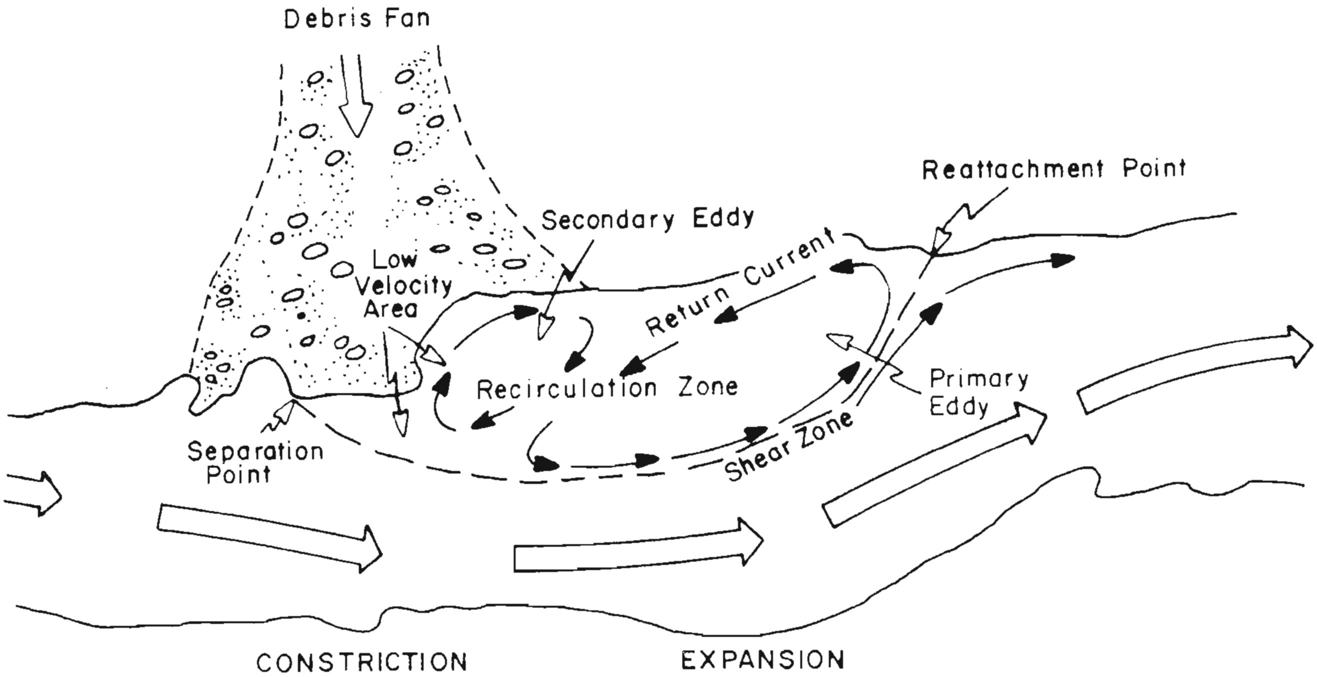


Figure A-3. Flow patterns at a relatively high discharge in a typical recirculation zone are composed of primary and secondary eddies. (After Schmidt and Graf 1987, Figure 3A) recirculating current (**recirculation zones**, Figure A-3) composed of one or more eddies develop where the channel widens downstream of this constriction.

Sand deposits may be located on the downstream surface of a debris fan and at the downstream end of a recirculation zone (Figures A-2 and A-4). Deposits located on the downstream surface of the debris fan are typically steeper than other sand deposits and extend to higher elevations. Flow velocity in the vicinity of these deposits is typically less than elsewhere in the recirculation zone. These deposits are called **separation deposits** because they are located at the upstream end of the recirculation zone where downstream-directed flow begins to separate from the channel banks (Figure A-3). Boaters use this type of deposit as campsites more frequently because low flow velocities make mooring of boats easier, and high elevation sand deposits provide campsites which are less likely to be inundated by rising water level than lower deposits. Sand deposits located at the downstream end of a recirculation zone are broader but lower in elevation than separation deposits. These are called **reattachment deposits** (Figure A-2 and A-5) because they form near the point where downstream-directed flow reattaches to the channel bank (Figure A-3). Boaters use these deposits as campsites only when they are of sufficiently high elevation to prevent inundation. Typically, this only occurs in wide reaches of Grand Canyon.

Low-elevation areas are found between separation and reattachment deposits in recirculation zones that contain sand (Figure A-2 and A-5). Under some flow conditions, these areas may become low-velocity, warm-water habitats (called **backwaters**) used for rearing of native fishes.

The rapids for which the Colorado River is famous are formed by very coarse sediment (boulders) transported to the river by flows in steep tributaries within Grand Canyon. The high flow velocities and large waves which make navigation of rapids a challenging and exciting recreational experience are created by the channel constriction and roughness formed by the debris fan and boulders delivered by tributary debris flows (Figure A-6).

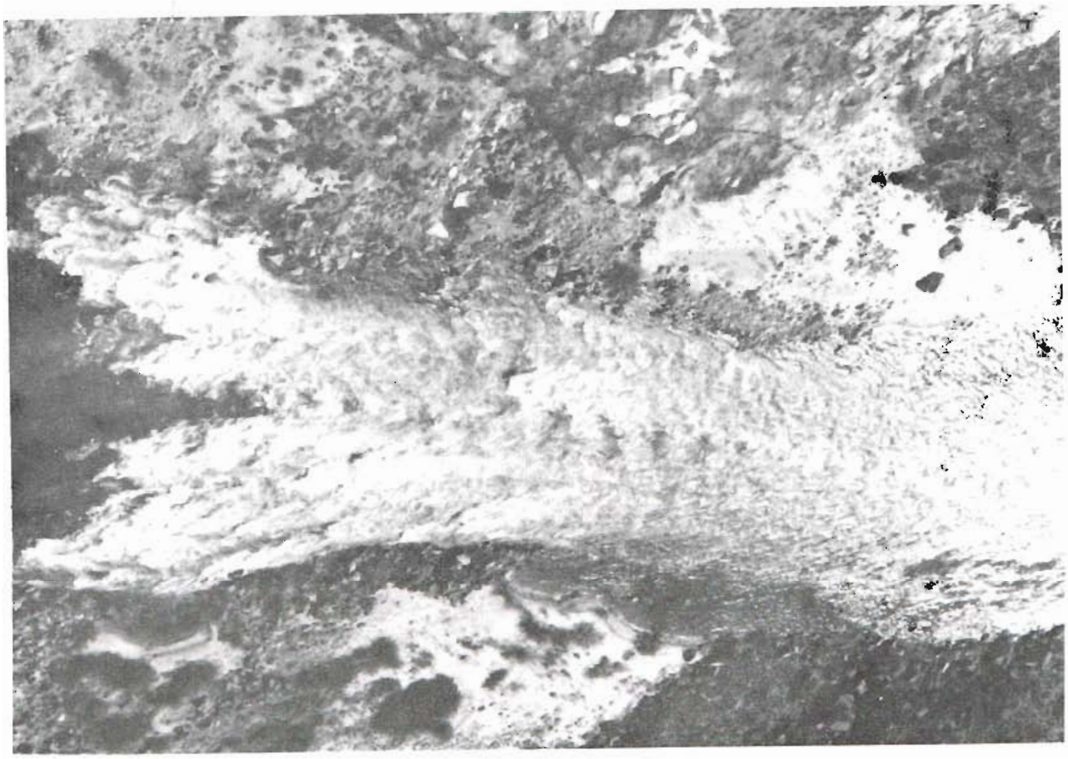


Figure A-4. Separation deposits downstream from Badger Creek Rapid (River Mile 7.9). Separation deposits mantle Jackass Creek debris fan in the top of the photo and Badger Creek debris fan on the bottom of the photo. Flow from left to right.

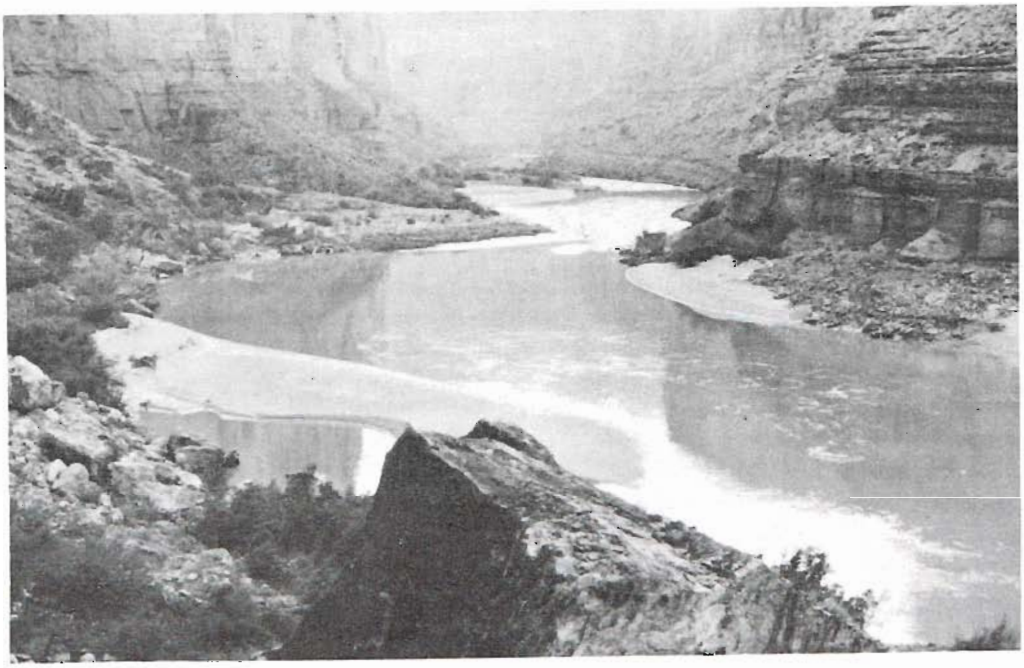


Figure A-5. Downstream view at Eminence Break Camp (River Mile 44.2) at a discharge of 5,000 cfs (October 1985). At the left bank is a reattachment deposit and an associated backwater. At the right bank is a channel margin deposit. (Schmidt and Graf 1987, Figure 18)

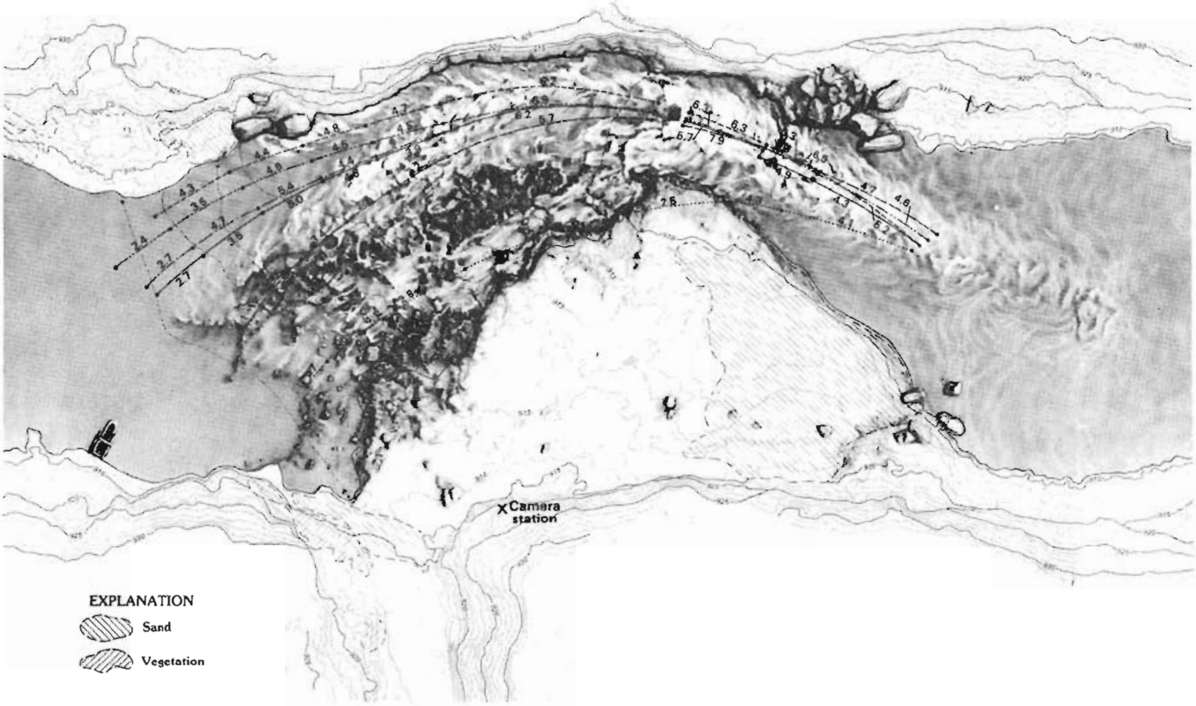


Figure A-6. Preliminary hydraulic map of House Rock Rapid (River Mile 16.9) showing velocities and streamlines at 5,000 cfs. Flow direction is from left, scale is 1:2000. Contour intervals indicated with solid lines are 1 meter and those with dashed lines are 0.5 meters. Numbers indicate velocities along streamlines between the adjacent dots; velocities are in meters per second. (After Kieffer 1987b, Figure 10d)

Study Objectives

The seven objectives established for the sediment studies were: (1) identify the reaches of the river that are losing, gaining, or are in equilibrium with respect to sedimentation; (2) identify the source of sand in transport; (3) determine the present net sand outflow from Grand Canyon into Lake Mead; (4) identify specific campsite beaches that are gaining, losing, or in equilibrium; (5) determine potential management actions to reduce or halt campsite beach erosion; (6) estimate what the river morphology would be like up to 100 years from now based on operational alternatives; and (7) expand and refine the existing flow routing model, particularly in riparian habitat areas. Brief summaries of findings related to specific objectives are given under **Major Findings**, and sections of the report deal in greater detail with the basis for findings related to study objectives.

Study Design

Nine studies related to sediment and hydrology were developed to address the objectives through study of main channel processes, camping beaches, and tributary sediment delivery. Studies were made by individuals from the Bureau of Reclamation (BOR), the U.S. Geological Survey (USGS), and consultants to the BOR and to the National Park Service (NPS). Results of these individual studies are integrated in this report and provide a basis for evaluating the effects of flow on sediment resources and for determining the long-term impacts of current operations on resources. Studies are outlined in this section, and Table A-1 shows the objectives addressed by each study.

<u>Studies of main channel processes focused on sand storage and transport.</u> Large variations in dam releases during the day produce hydrographs with well-defined peaks and troughs (see GCES Final Report, Figure V-3). Peaks become lower and broader as flow moves downstream. Knowledge of the relation between water surface elevation and discharge at points downstream from the dam was required for GCES recreation and biology studies as well as for the sediment studies. Lazenby (1987) used an iterative process to calibrate an unsteady flow model with data for fluctuating flows from October 1985 to January 1986 for each of five USGS stream gaging stations (Figure A-1). Estimates of discharge made with the calibrated

Table A-1. Individual sediment and hydrology studies and study objectives addressed.

STUDIES (Author, Affiliation)	OBJECTIVES 1 Identify Reaches	2 Identify Sources	3 Determine Outflow	4 Identify Beaches	5 Management Actions	6 Long-Term Condition	7 Flow Routing Model
Historical Gaging Station Analysis (Burkham, NPS)	X				X	X	
Sediment Data Collection and Analysis (Pemberton, BOR)	X	X	X			X	
Bed Materials (Wilson, USGS)	X	X					
Debris Flows (Webb et al., USGS)		X				X	
Flow Routing Model (Lazenby, BOR)	X		X		X		X
Sediment Transport Modeling (Randle & Pemberton, BOR) (Orvis & Randle, BOR)	X	X	X		X	X	
Alluvial Sand Deposits (Schmidt & Graf, USGS)	X			X	X	X	
Beach Surveys (Ferrari, BOR)				X	X	X	
Rapids and Waves (Kieffer, USGS)					X	X	

model were used in sediment transport modeling that was a part of these studies.

An analysis of data collected during discharge measurement at USGS gaging stations at Lees Ferry, just above the Paria River, and near Grand Canyon, just above Bright Angel Creek (Figure A-1), was aimed at understanding the effect of flows on sand stored in main channel pools and on coarse material in riffles and rapids (Burkham 1987). Burkham examined bed elevation in the gaged section, mean velocity, the relationship between water surface elevation and discharge, and the relationship between velocity and discharge from 1922 to 1984 at the two gaging stations. The study yielded a general understanding of sand storage changes in these pools, and discharges necessary to degrade the channel bed within the pool and to adjust riffles following addition of material by tributary flows.

Sediment and flow data were collected at the two gages used by Burkham and at three additional gages (Figure A-1) for about six months in 1983 and about four months in 1985-1986. A total of 874 discharge measurements were made, and 1,943 suspended sediment and 976 bed material samples were collected during those two periods. Data were used to develop the relationships between sand transport and discharge (Pemberton 1987) and to evaluate channel hydraulics at the gaged sections (Randle and Pemberton 1987). Data also provided information on sand transport and storage during the study period. Sand transport relationships, bed material size distribution, and channel hydraulics were used in the sediment transport modeling discussed below.

A knowledge of the amount and size distribution of materials on the channel bed was required for a complete understanding of sand transport and storage changes. Bed materials within recirculation zones, which were relatively easy to sample because much of the sand was exposed at low flow, were described by Schmidt and Graf (1987). Sampling to identify bed materials within the main channel between gaging stations was much more difficult because of high velocities and deep water, and was done on a limited scale. Geophysical methods, including seismic reflection, side-scan sonar, and echo depth sounder were combined with examination of aerial photographs taken at low flow and samples of bed material to develop maps of broad categories of bed materials for about 75 percent of the 225-mile study reach (Wilson 1986).

Actual measurement of sand transport and storage changes at gaging stations could be made at only five locations over a limited time span and flow characteristics. Sediment transport modeling provided a framework for extension of information gained from direct measurement and sampling. Two types of sediment transport models were used. The Sediment Transport and River Simulation Model (**STARS**), a sediment routing model, provided a simulation of water and sediment movement through the channel, cross section by cross section. This model combined the procedure of computing river channel hydraulics with sand transport relationships to predict movement of sand for any pattern of discharges. A unique feature of this one-dimensional, steady flow model was the ability to account for variations in bed material across the channel. Fluctuating flows were approximated by steps of steady discharge. The model made adjustments if sand supply was less than computed transport capacity. The characteristics of the sediment routing model are described by Orvis and Randle (1987) and the application of the model to the Colorado River by Randle and Pemberton (1987).

The Sediment Transport Analysis Budget model (**STAB**), developed for GCES, computed the loss or gain of sand in reaches between Glen Canyon Dam and the five gaging stations. Sand transport was computed using the sand transport relationships developed from measurements at those gages and on the three largest tributaries, as well as from estimates of sand delivered by ungaged tributaries. This is a mass-balance model: for any given time, loss or gain of sand in a reach between two gages is assumed to be equal to computed amount of sand entering the reach minus computed amount leaving. STAB model characteristics and application to the Colorado River are given by Randle and Pemberton (1987).

The geometric and hydraulic characteristics of rapids in Grand Canyon were poorly known prior to 1983. Main channel flow and debris flows in tributaries can significantly alter the channel geometry in the vicinity of rapids and change the flow velocity and pattern of waves. Kieffer (1985; 1987b) described the channel geometry and hydraulics at 12 of the largest rapids. Definitions were given to hydraulic and geomorphic features in rapids, a generalized hydraulic model for rapids was developed, and hydraulic maps at two or three different discharges at ten of the twelve rapids were drawn (Figure A-6) (Kieffer 1985; 1986;

1987a; 1987b). Kieffer has provided insight into discharges necessary to move large debris in rapids.

Studies of camping beaches, vegetation substrate, and backwaters focused on understanding the relationship of sand deposit change to flow. Specific studies of sand deposits used as campsites and substrate for vegetation and fish habitat were designed to provide a framework for understanding the complex changes which these deposits undergo as a result of flows. About 41 deposits selected for study were surveyed and important channel and flow characteristics measured. Measured characteristics include channel width, depth, and slope, speed and direction of currents, water surface slope, size and steepness of alluvial fans, size and shape of zones of recirculating current, size, shape and position of sand deposits, and grain size distribution of material on the bed and banks of the river. Deposits were classified using channel and flow characteristics which were found to be most influential in determining the location of deposits and changes caused by flow. Characteristics of sand deposits which revealed the conditions of deposition were examined. Information obtained from direct measurements during the study period was combined with information from analysis of historical photographs and surveys to develop the conceptual model of sand deposit location and change presented in this report. Results are given in Schmidt and Graf (1987) and Schmidt (1987). In addition, baseline surveys of important camping beaches were made and compared to earlier surveys of those beaches (Ferrari 1987).

Studies of tributaries focused on estimating the amount of sand delivered to the Colorado River. Data from gaging stations on the three largest tributaries, the Little Colorado and Paria Rivers and Kanab Creek (Figure A-1), were used to develop sand transport relationships (Randle and Pemberton 1987). Transport relationships were then used with daily discharge values to compute sand delivery for these tributaries for the periods of interest (Randle and Pemberton 1987). A reconnaissance study was made to evaluate the importance of sand delivery from the 310 ungaged tributaries in Grand Canyon (Webb, Pringle, and Rink 1987). Thirty-six tributaries were examined, and detailed study of debris flow deposits in three ungaged tributaries yielded information on the magnitude and frequency of debris flows.

Major Findings Related to Objectives

Major study findings which relate directly to the seven objectives are summarized below. References to later sections are given in the summaries to direct the reader to additional detail or support for statements.

(1) Loss or gain of sand in reaches depends on many factors and therefore varies with time. These factors include the amount of sand delivered by tributaries within Grand Canyon, the amount of sand stored in the main channel pools, and the peak and volume of flow. STARS and STAB model results indicate that sand will accumulate in reaches between the USGS gaging stations at Lees Ferry and near Grand Canyon at flows within the powerplant range, if annual volume is less than about 12 million acre-feet (maf) and tributary delivery of sand is average. According to the STAB model, reaches below the Grand Canyon gage are stable. The STAB model estimates show loss of sand during flood flows of 1983-1985 from reaches above the Grand Canyon gage and either a small gain of sand or no change in reaches below that gage (Randle and Pemberton 1987). However, model results have considerable uncertainty (see Section V), and limited field data provide some evidence that contradicts model results. Therefore, our current knowledge of sand storage changes along the river is poor. Loss or gain of sand from camping beaches, vegetation substrate, and backwaters varies with deposit type and local channel geometry in addition to the factors which control loss or gain from main channel pools.

(2) Most sand is delivered by the three largest tributaries. The primary sources of sand transported by the Colorado River in Grand Canyon are Kanab Creek and the Paria and Little Colorado Rivers. The contribution of sand from other tributaries, where debris flows and hyperconcentrated flows are important mechanisms of transport, is smaller, but may be significant.

(3) Net loss of sand from Grand Canyon is highly variable. Net sand loss from Grand Canyon varies with time, depending on flow, the amount of sand stored in the channel, and the amount of sand delivered to the river by tributaries. STAB model results suggest that if tributary sand supply is average, sand will be gained in low flow years, such as 1982, and lost in high flow years, such as 1983 to 1986. An estimated

15.4 million tons (mt) of sand were lost from Grand Canyon in the time period of 1983 to 1986.

(4) <u>Camping beaches in narrow reaches and on reattachment deposits are particularly susceptible to erosion.</u> Beaches used as campsites are found primarily on two types of sand deposits, which differ in their susceptibility to erosion. Campsites in narrow reaches are more susceptible to erosion than those in wide reaches, and the susceptibility to erosion of a specific campsite beach within both narrow and wide reaches depends on the type of deposit and local channel geometry. Camping beaches in the reach above the Little Colorado River are more susceptible to loss than those below that confluence because the Little Colorado River is the largest source of sand to the system. Campsites on reattachment deposits, formed in the downstream parts of recirculation zones, are more susceptible to erosion than those on separation deposits, which mantle the debris fan at the upstream end of the recirculation zone. Although results of this study provide an estimate of the likelihood of loss of sand from specific camping beaches, they do not allow us to determine whether individual campsite beaches other than those specifically studied are losing or gaining sand.

(5) <u>Floods should be avoided to preserve beaches for as long as possible.</u> The most significant management option to reduce erosion of camping beaches is to avoid floods (releases greater than powerplant capacity for a month or more).

(6) <u>Current operations will result in loss of some beaches in the long-term.</u> Under current operations, with flood releases expected one of every four years, there will be loss of sand-dependent resources in the long-term. Rate of loss will be greatest in the next 10 to 20 years, and greatest in narrow reaches and upstream of the Little Colorado River. Modified dam operations could limit the amount of loss. Under all operation options, rapids may become more difficult to navigate because flows would be incapable of completely removing all coarse debris added by tributary debris flows. However, our lack of knowledge of future tributary sand input, channel changes, and flow conditions, and the lack of understanding of interactions between sand in the main channel and sand in beaches prevent us from being able to predict what river morphology will be like in 100 years.

(7) Flow routing model was recalibrated. The existing flow routing model has been recalibrated with flows from the study period, resulting in a more accurate estimate of flows in Grand Canyon than was previously available. However, model results are subject to significant uncertainties (see Section V) and are dependent on the particular flow and channel conditions for which the model was recalibrated. Estimates made with the model will become poorer as channel and flow conditions depart from those of the calibrated period.

Other Major Findings

In addition to answers to objectives outlined at the onset of the sediment studies, several significant findings have resulted. These are given below.

Frequent flows higher than 31,500 cfs will severely deplete sand stored in the main channel, and that depletion may eventually cause loss of campsites.

Main channel transport of sand within powerplant capacity is only slightly higher under fluctuating flow than under steady flow of the same volume. Sediment transport modeling shows that for an annual flow volume of 8.2 maf, fluctuations up to the powerplant capacity of 31,500 cubic feet per second (cfs) produce only about 12 percent higher transport than steady flows of that volume. The effect of this difference in main channel transport on the long-term stability of camping beaches could not be determined in this study.

Availability of campsites, and backwater areas for fish, is less under fluctuating flow, especially in narrow reaches. Area available for camping depends primarily on the maximum flow, which is higher for fluctuating flow than steady flow with the same volume of release. Steady flows which inundate reattachment deposits create deep return flow channels and high reattachment deposits if sand is in sufficient supply. Fluctuating flows tend to smooth out topography within recirculation zones, reducing the size and areal extent of backwaters.

Sand deposits will reach a relatively stable condition after a change in type of flow. Onset of flow fluctuations or lower, steady flow after a period of high, steady flow causes erosion of sand deposits throughout Grand Canyon initially, but rate of erosion decreases rapidly.

Change from one type of dam operation to another increases the chance of loss of sand from camping beaches. Sand deposits readjust to changes in dam operations, but each readjustment subjects beaches to possible loss.

Tributary debris flows may create large and difficult rapids, and flows much greater than powerplant capacity may be required to adjust those new rapids to more navigable conditions. Because maximum flows have been greatly reduced by flow regulation, much of the very coarse debris deposited near tributary mouths cannot be moved under current operations. Rapids may become more difficult to navigate, and more unsafe, as a result of buildup of debris.

Buildup of debris at rapids may significantly change the hydraulics of the river. Large changes in channel width, elevation, and roughness at riffles and rapids change the hydraulics of the channel locally and may have significant implications to sand transport and storage.

Organization of the Report

Section II describes the processes of sediment transport and storage in Grand Canyon that affect the stability of sediment resources under different flow conditions.

Section III sets out predictions concerning the future of sediment-related resources should the dam continue to be operated as it is currently.

Section IV presents a modified operation scenario which would protect sand resources and evaluates the response of sediment resources to scenarios developed to protect other resources.

Section V is a comprehensive discussion of the limitations in data and methods used to reach some of the findings in the report.

Section VI is an outline of recommendations for future monitoring and research developed to address the gaps and uncertainties summarized in the previous section.

SECTION II: SEDIMENT TRANSPORT AND STORAGE

Sand Transport and Storage

In some reaches, rocks through which the river flows are very resistent to erosion and the river runs in a narrow channel bounded by rock walls. In other reaches, the river has been able to erode less resistent rocks and flows in a relatively wide channel bounded by sand and gravel deposits. Wide and narrow reaches alternate throughout the length of the study area. Informal names given to reaches reflect the importance of rock type on reach characteristics (Table A-2, column 2). The ratio of width to depth of flow at a discharge of 24,000 cfs (Table A-2, column 3) for reaches shown on Figure A-1 shows that the river channel in narrow reaches is usually deeper than that in wide reaches. Water surface slope is also greater in narrow reaches than in wide reaches (Table A-2, column 6).

Stream power, which is directly related to velocity of flow, depth, and water surface slope, is shown in Table A-2 as a measure of sediment transport capacity (Vanoni 1975). Estimates of unit stream power (stream power per foot of channel width) for reaches in Grand Canyon (Table A-2, column 7) show that stream power is generally greater in narrow reaches than in wide reaches. Therefore, for the reaches shown, the capacity to transport sand is greater in narrow reaches than in wide reaches. As discharge increases, flow width in wide reaches increases at a greater rate than in narrow reaches, because the rock walls which bound narrow reaches constrain the flow. Therefore, for the same increase in discharge, the water surface elevation and stream power rises more in narrow reaches than in wide reaches. Maps of the materials which covered the channel bed (**bed materials**) in 1984 (Wilson 1986) show that a greater percentage of the bed in narrow reaches was covered by coarse boulders or bedrock than was covered in wider, shallower reaches (Table A-2, column 8).

In both narrow and wide reaches, channel characteristics change in the vicinity of debris fans that form at the mouths of steep tributaries (Figure A-6). The channel is shallower, narrower, and steeper around the debris fan than it is upstream or downstream. The channel bed of rapids is primarily composed of boulders. These shallow, steep reaches are the rapids and riffles of Grand Canyon.

Table A-2. Characteristics of the reaches within the study area.

Reach Number[1]	Local Name of Reach	Average Ratio of Top Width to Mean Depth[2]	Average Channel Width[2] (ft)	Description of Width Characteristic	Channel Slope[3] (ft/ft)	Average Unit Stream Power[4] (lb/ft-s)	Percentage of Bed Composed of Bedrock and Boulders[5]
1	Permian Section	11.7	280	wide	0.00099	5.3	42
2	Supai Gorge	7.7	210	narrow	0.0014	10.2	81
3	Redwall Gorge	9.0	220	narrow	0.0015	10.2	72
4	Lower Marble Canyon	19.1	350	wide	0.0010	4.3	36
5	Furnace Flats	26.6	390	wide	0.0021	8.0	30
6	Upper Granite Gorge	7	190	narrow	0.0023	17.8	62
7	Aisles	11	230	narrow	0.0017	10.9	48
8	Middle Granite Gorge	8.2	210	narrow	0.0020	14.2	68
9	Muav Gorge	7.9	180	narrow	0.0012	9.9	78
10	Lower Canyon	16.1	310	wide	0.0013	6.2	32
11	Lower Granite Gorge	8.1	240	narrow	0.0016	10.2	58

1 See Figure A-1.
2 Average of cross section data at about 1-mile intervals at 24,000 cfs (Randle and Pemberton 1987).
3 Based on predicted water-surface elevations at 24,000 cfs (Randle and Pemberton 1987).
4 Unit stream power is calculated as equal to the following:
(specific weight of water) (24,000 cfs) (slope of reach)/(average channel width).
5 From channel bed material maps (Wilson 1986).

The average river slope through Grand Canyon is about 8 feet per mile (0.0015 ft/ft). Slope may be ten times steeper at major rapids (Leopold 1969). Velocity in major rapids may be as great as 25 feet per second (ft/s) (Kieffer 1987). In contrast, low-slope (about 0.5 foot per mile [0.000095 ft/ft]), low-velocity areas exist between rapids where water depth may exceed 100 feet (ft) at some locations (Wilson 1986).

<u>Most camping beaches are sand deposits within recirculation zones.</u> Sand stored within recirculation zones is important because parts of these deposits are the major camping beaches within Grand Canyon. As described in the introduction, these zones are areas along the margins of the river channel where part of the flow moves upstream. In a channel such as the Colorado River in Grand Canyon, where the banks are typically composed of bedrock or large rock debris, these zones are found where debris flows create fans that form abrupt constrictions and downstream expansions of the channel (Figures A-2 and A-3).

The pattern of sand storage within recirculation zones is distinctive. Sand typically is located at the upstream end of the zone on the downstream-facing surface of the debris fan which forms a rapid or riffle upstream of the recirculation zone (**separation deposits**) (Figures A-2 and A-4). Sand is also located near the downstream end of the recirculation zone (**reattachment deposits**). Reattachment deposits typically project upstream and may fill much of the recirculation zone (Figures A-2 and A-5) (Schmidt and Graf 1987).

The number and size of recirculation zones varies along the river corridor. Between Lees Ferry and Bright Angel Creek (River Miles 0 to 87), the number of recirculation zones varies between 2.3 and 4.5 per mile (Table A-3). The average size of reattachment deposits exposed at a discharge of about 6,000 cfs in 1984 between Lees Ferry and the Little Colorado River (River Miles 0 and 61) and between River Miles 118 and 160 ranged from 2,300 to 87,000 square feet (Table A-3). Typically, larger reattachment deposits were associated with the larger recirculation zones of wide reaches.

Table A-3. Characteristics of recirculation zone deposits in selected reaches.

Reach Number[1]	Campsites per Mile[2]	Primary Type of Sand Deposit Used as Campsite[3]	Number of Recirculation Zones per Mile	Average Size of Deposits[4] (ft^2)	Average size of Separation Deposits[4] (ft^2)	Average size of Reattachment Deposits[4] (ft^2)	Total Area of Major Deposits[4,5] (ft^2)
1	0.4	separation	3.2	51,000	57,000	31,000	410,000
2	0.9	separation	3.6	23,000	30,000	16,000	510,000
3	0.9	separation	4.5	25,000	21,000	47,000	540,000
4	2.6	separation reattachment	4.5	60,000	49,000	87,000	4,700,000
5	2.5	channel margin	2.3	NE[6]	NE	NE	NE
6	0.6	separation channel margin	2.7	NE	NE	NE	NE
7	3.2	reattachment separation channel margin	NE	25,000	26,000	35,000	920,000
8	2.3	channel margin	NE	22,000	17,000	34,000	900,000
9	1.1	channel margin	NE	8,200	14,500	2,300	240,000
10	2.4	NE	NE	NE	NE	NE	NE
11	2.3	NE	NE	NE	NE	NE	NE

1 See Figure A-1.
2 Inventoried by Brian and Thomas 1984 (Schmidt and Graf 1987, Table 2).
3 Listed in order of importance (Schmidt and Graf 1987, Table 2).
4 Measured area is that exposed at about 6,000 cfs in October 1984 (Schmidt and Graf 1987, Table 7).
5 Major deposits are those alluvial sand deposits inventoried as campsites in 1973 or 1984, as well as other deposits located in the same recirculation zones. Major deposits are located in about 45 percent of all recirculation zones.
6 Not evaluated.

Only those sand deposits high enough in elevation to be safe from inundation and large enough to accommodate at least a small group of people are used as campsites. All types of sand deposits are used as campsites: separation, reattachment, and channel margin deposits. Campsites were inventoried in the fall of 1983 at a discharge of 28,000 cfs, and the number of campsites per mile was found to range from 0.4 to 2.6 (Table A-3). Although the variation in number of deposits along the river differs with deposit type, the number of campsites was typically greater in wide reaches than in narrow reaches. Therefore, wide reaches of the river are characterized by a greater number and larger size of sand deposits useable as campsites.

The characteristic topography of separation and reattachment deposits affects the size of deposits available for camping at different discharges. Large parts of many separation deposits are not inundated until discharge exceeds 30,000 cfs. Reattachment deposits, in constrast, are typically broad and low in elevation and are inundated at relatively low discharges. For this reason, separation deposits are more attractive as campsites. For example, at nine separation deposits studied in detail (Schmidt and Graf 1987, Table 14) the average area of sand inundated during an increase in discharge from about 6,000 to about 25,000 cfs is 14,000 square feet. In contrast, at six reattachment deposits an average of about 50,000 square feet is inundated over the same discharge range. The area of separation deposits inundated is about 30 percent of the total area of each separation deposit. Most reattachment deposits are inundated at discharges within the powerplant range, whereas parts of many separation deposits are still exposed at a discharge of 45,000 cfs.

<u>Main channel pools are also important sand storage sites.</u> Sand stored in relatively low-elevation reaches of the main channel (**main channel pools**) may be important to stability of camping beaches and vegetation because it may be available to replenish sand in recirculation zones under some conditions. Burkham (1987) has shown that at the USGS gaging stations at Lees Ferry and near Grand Canyon, bed elevation in pools changed as much as 20 ft and 8 ft, respectively, before flow regulation. Before the dam was constructed, bed elevation decreased as sand and gravel were scoured from the bed during annual snowmelt runoff (Burkham 1987). Peak flow during this runoff averaged about 93,400 cfs (U.S. Geological Survey a and

b, issued annually). Sand and gravel were deposited on the bed at lower flows at other times of the year, and bed elevation increased as this deposition progressed (Burkham 1987). The amount of stored sand available for transport, therefore, depends on both flow and preceding bed elevation.

A rough estimate of the amount of sand stored in 1984 in the main channel and in recirculation zones between the gages at Lees Ferry and near Grand Canyon was made. This amount, 42 mt, was estimated by multiplying the surface area of sediment (Wilson 1986) by the percent sand in those deposits and an assumed deposit thickness of 20 ft (Randle and Pemberton 1987). The bed material maps were made from a geophysical survey of the channel bed made in March 1984. Because this survey closely followed the record post-dam discharges reaching 97,200 cfs at Lees Ferry in June 1983, some of the sand remaining in the bed at the time of the survey may not be available for transport at discharges in the powerplant range. Burkham (1987) concluded from his analysis of hydraulic data at gaging stations that most of the sand on the bed after the 1983 flood was not available for transport at flows within the powerplant range. Randle and Pemberton (1987) have used the STAB model to estimate that 6.6 mt of sand were lost from the reach between the two gages between January 1984 and October 1985. This suggests that some sand on the bed in 1984 was available for transport under the flood releases of 40,000 to 50,000 cfs in the summers of 1984 and 1985 (Figure A-7).

Tributary Sediment Delivery

Before construction of Glen Canyon Dam, sand to replenish that scoured from within Grand Canyon was supplied from the watershed above the dam and from tributaries within Grand Canyon. Since completion of the dam, sediment from upstream of the dam has been trapped in Lake Powell, hence sediment loads in Grand Canyon have greatly decreased. Annual total suspended-sediment load (sand, silt, and clay) past Lees Ferry decreased from 65.4 million tons per year (mty) in the period 1948 to 1962 (U.S. Geological Survey a and b, issued annually) to about 0.4 mty in 1982 and 1986 (Graf and Burkham In preparation).

The source of resupply of sand to channel pools and recirculation zones is now the tributaries which enter the river downstream of the dam. Analysis of gaging station records (Randle and Pemberton 1987) and

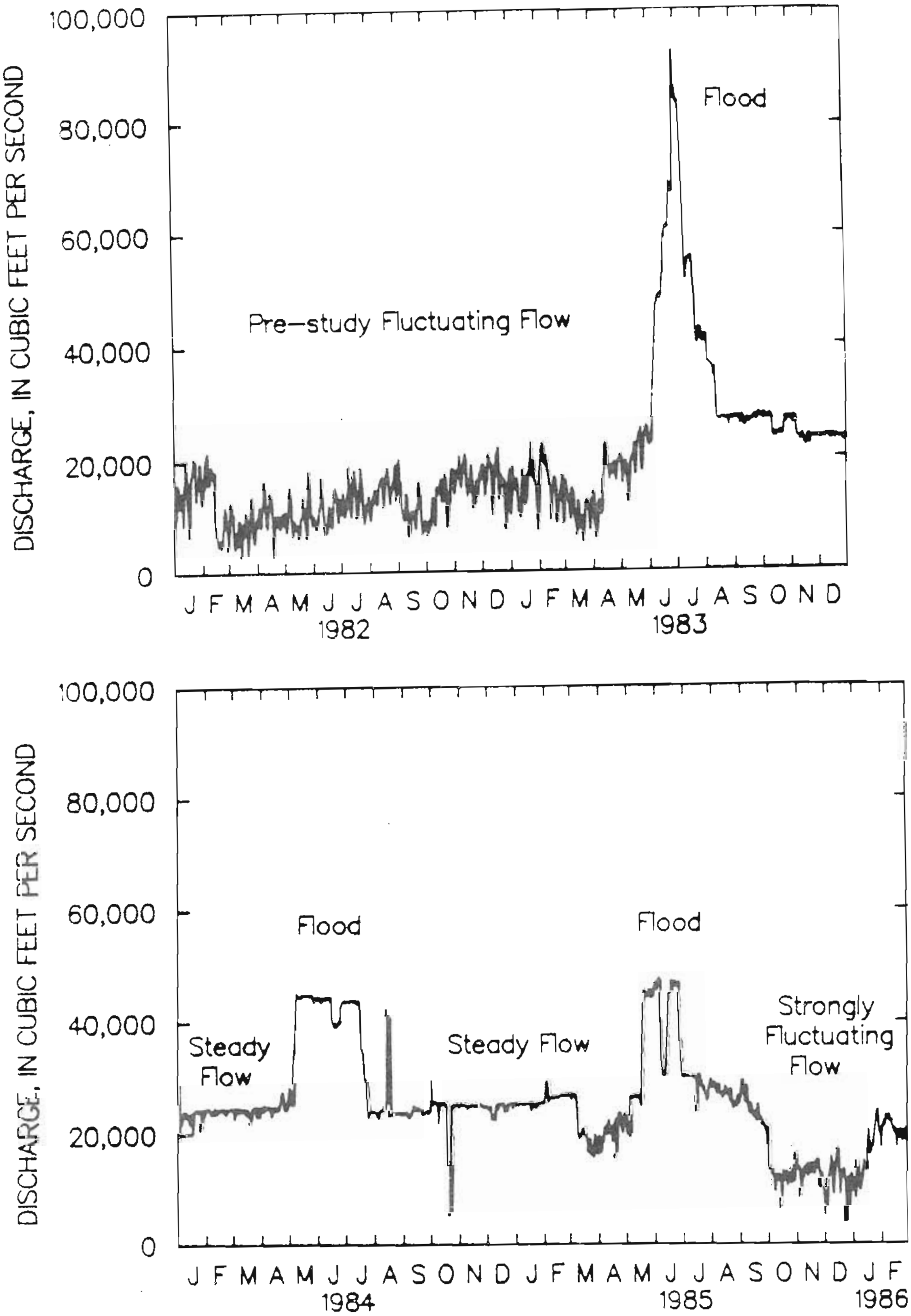


Figure A-7. Mean daily flows during the study period (June 1983 to January 1986) included three floods, nearly steady flows near the peak of powerplant releases, and a short period of strongly fluctuating releases that were similar to pre-study flows in 1982-83. (After Schmidt and Graf 1987, Figure 9) data from geomorphic analysis of deposits from small tributaries (Webb, Pringle, and Rink 1987) indicate that the primary source of sand to the river is the Paria and Little Colorado Rivers and Kanab Creek. Together, these three tributaries supply an estimated 2.9 mty of sand (Randle and Pemberton 1987). This value for sand delivery was computed using average sediment transport-discharge relationships computed from samples collected over the entire period of sampling for those three tributaries and for Moenkopi Wash, a tributary to the Little Colorado River which enters downstream of the Little Colorado River gaging station. However, sediment contribution from these tributaries is highly variable, and may vary from year to year as much as an order of magnitude. For example, annual total suspended sediment loads in the Little Colorado River averaged 10.1 mt in the period 1958 to 1970, but ranged from 3.5 mt to 19.1 mt (U.S. Geological Survey a and b, issued annually). Also, sediment delivery from the Little Colorado and Paria Rivers is probably subject to long-term variations related to variations in sediment storage in floodplains of these streams (Hereford 1984; Hereford, Richard, 1987, USGS, Flagstaff, Arizona, Pers. Comm.). These three major tributaries supply large amounts of silt and clay as well as sand. Some flows on the Paria and Little Colorado Rivers can deliver total suspended sediment loads containing as much as 99 percent silt and clay (U.S. Geological Survey a and b, issued annually; Pemberton 1987). Typically, the Colorado River can transport most of this fine material downstream, although silt and clay may be deposited on channel banks under some conditions.

Smaller tributary canyons typically form at locations of structural weakness in the rocks (areas of faulting or jointing) (Dolan, Howard, and Trimble 1978). A reconnaissance study of drainage basins of tributaries other than the Paria and Little Colorado Rivers (Webb, Pringle, and Rink 1987) showed that much of the sand and coarser debris from these other tributaries is delivered to the river by flows known as **hyperconcentrated** or **debris flows**, which are very concentrated mixtures of sediment and water. Debris flows typically contain only 15 to 40 percent water by volume and hyperconcentrated flows, only 40 to 80 percent water. Debris and hyperconcentrated flows transport different sizes and amounts of sediment, and a single tributary flow event may be made up of a complex series of pulses of these two types of flow (Figure A-8). (See Webb, Pringle, and Rink 1987.)

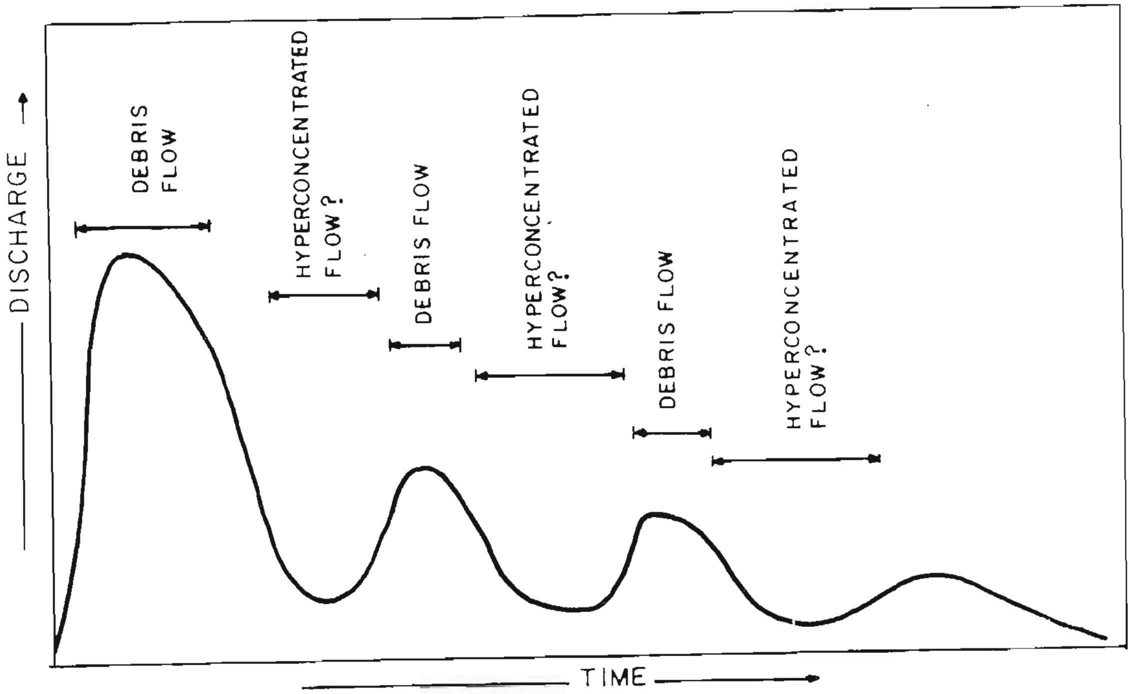


Figure A-8. A single debris flow event down a steep tributary valley may be composed of several pulses of debris and hyperconcentrated flow within a short period of time. (After Webb, Pringle, and Rink 1987, Figure 12)

The occurrence and size of these flows is influenced by geologic and geomorphic conditions within the watershed and prior history of flows, as well as by rainfall amount and intensity. Slope failures in these steep tributary valleys commonly trigger debris flows. Webb, Pringle, and Rink (1987) found evidence of debris flows within the last 25 years in 21 of 36 tributaries investigated. Debris flows which reached the river were found to have occurred at least once in the last 15 to 50 years in the three drainages which were studied in some detail. Debris flows studied contained material that ranged in size from boulders to clay, with sand content of samples ranging from 10 to 40 percent. Estimates of sand delivered to the river by a debris flow which occurred in Monument Creek in 1984 ranged from 2,800 to 7,300 tons. (See Webb, Pringle, and Rink 1987.)

The variability of debris flow occurrence and the absence of a general model for magnitude and frequency of these flows make it difficult to estimate the long-term rate of delivery of sand to the Colorado River from the 310 ungaged tributaries. A drainage basin/sediment yield relationship applicable to streamflow-dominated systems was used to provide an estimate for this study (Randle and Pemberton 1987). Using this method, 0.7 mty of sand were estimated to be delivered to the river. Ungaged tributaries were estimated in this way to contribute about 20 percent of the total sand delivered in an average year.

Processes in Main Channel Pools

Computations of sand transport and bed change with the STARS model (Randle and Pemberton 1987) and analysis of data from the USGS gaging stations at Lees Ferry and near Grand Canyon (Burkham 1987) give evidence on the nature of transport and storage of sand in the main channel. STARS model computations at 199 measured cross sections indicate that sand is transported through most channel pools at flows exceeding 15,000 cfs, when mean velocities at these locations are typically about 3 to 4 ft/s. Analysis of long-term (1922-1984) changes in elevation at the point of maximum depth in the two gaged cross sections indicates that when the bed was at a high elevation, bed degradation was initiated at discharges of 16,000 to 20,000 cfs, when velocities reached about 5 or 6 ft/s (Burkham 1987). These slight differences in results are not considered significant.

As degradation of the bed progresses, the area of flow in the cross section increases and the mean velocity decreases (Burkham 1987; Randle and Pemberton 1987). For scour to continue, discharge must increase to keep the velocity above that required to degrade the bed. For example, at Lees Ferry, daily discharges of between 40,000 and 60,000 cfs for more than 40 days in 1965 degraded the bed about 27 ft. Because this gage is upstream of any significant tributary delivery of sand and gravel, the bed has not aggraded since 1965, and it would now take an estimated 70,000 cfs to initate further degradation at this section. The 1965 flow caused the bed at the gage near Grand Canyon to degrade to its historical low elevation (Figure A-9). However, addition of coarse sediment to the rapid downstream of the Grand Canyon gage combined with some supply of sediment from upstream, resulted in subsequent aggradation of the bed at that site (Figure A-9).

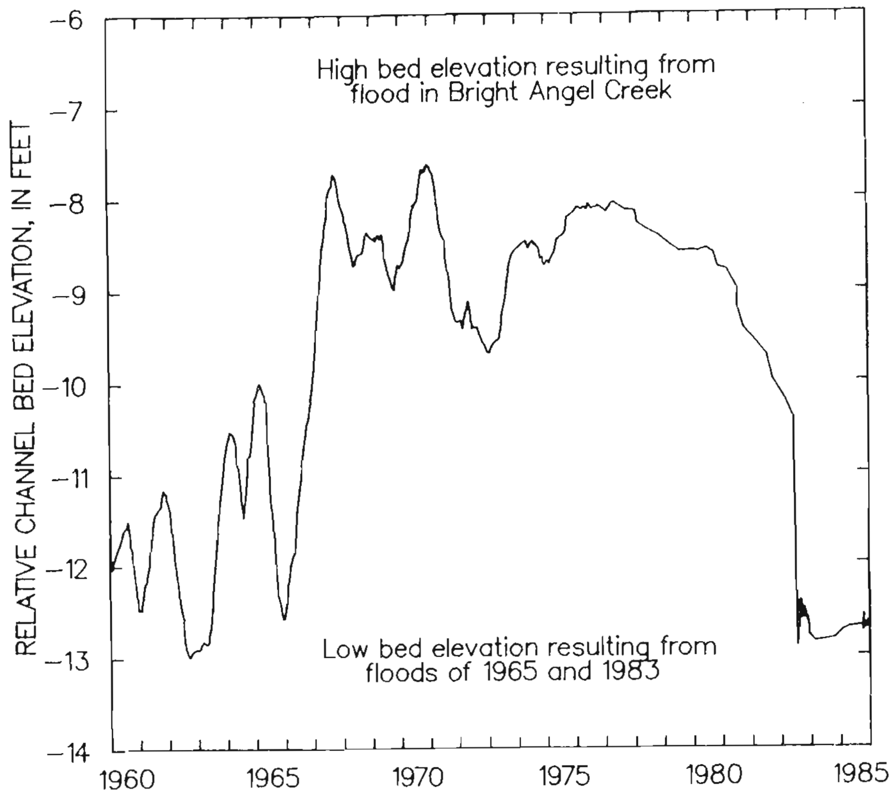


Figure A-9. Bed elevation at the USGS gaging station near Grand Canyon (River Mile 87). Bed elevation increased after flow from Bright Angel Creek (December 1966) added material to the fan and rapid downstream. Bed elevation decreased to pre-dam low condition during high flows of 1965 and 1983. (After Burkham 1987, Figure 7)

At some pools, such as the one at the Lees Ferry gage, degradation is limited both by the decrease in velocity caused by degradation and by increase in size of bed material (Burkham 1987). STARS model computations show that as degradation progresses, velocity decreases and bed material coarsens (Randle and Pemberton 1987).

The bed material, at some point, may become sufficiently coarse and velocity sufficiently low that flow is no longer capable of moving the material, and degradation stops. Pemberton (1976) has documented the coarsening of gravel bars in the reach upstream of Lees Ferry.

Sediment transport modeling and analysis of data from gaging stations demonstrate that flows less than maximum powerplant releases (31,500 cfs) are not capable of transporting all the sand delivered annually from tributaries, unless annual volume of flow exceeds 12 maf (Randle and Pemberton 1987). As pools continue to fill, the annual transport through Grand Canyon should approach the amount delivered annually by tributaries. When runoff is less than or equal to the average annual runoff (11.3 maf) and releases from Glen Canyon Dam are less than powerplant capacity, pools which are at relatively low elevations will aggrade. The time required to fill pools to an elevation which is stable for prevailing flow conditions depends on the volume of water released, the magnitude and duration of flow, and the amount of sand and gravel delivered by tributaries. Estimates of the time to fill main channel pools for given operations (Table A-4) made with the STAB model are based on average sand transport relationships and average annual rates of sand delivery from tributaries. The time necessary to refill degraded channel pools must decrease in the downstream direction as the number of sand-contributing tributaries increases. Modeling results indicate that the time to fill pools downstream of the Little Colorado River is approximately 40 percent of the time necessary to fill pools upstream of this major tributary.

Processes in Recirculation Zones

The pattern of sand storage within recirculation zones described in the introduction is determined by the typical pattern of flow circulation in these zones (Figure A-3). At low discharges, most zones are composed only of a primary eddy, and the separation deposit (Figures A-2 and A-3) is exposed. The reattachment deposit may fill much of the recirculation zone underneath the primary eddy (Figures A-2 and A-3). At higher discharges, the water surface elevation increases and additional areas are inundated. As flow inundates the separation deposit, smaller, lower-velocity secondary eddies are developed upstream of the return current channel (Figure A-3). Some areas upstream of the return current channel are inundated by flow of very low velocity with no distinct eddy circulation (Figure A-3). (See Schmidt and Graf 1987.)

Table A-4. Average annual sand deposition from River Mile 0 to River Mile 87 and relative time to fill main channel pools to 1982 elevation. Deposition rates are computed based on three years of low flow (8.31 maf) and one year of high flow (16.6 maf) following the scour of an estimated 15.6 million tons in 1983-1986. Relative times were computed by dividing the computed time to fill, in years, by the time to fill under current operations.

Flow Alternative	Average Annual Deposition From STAB Model (millions of tons)	Relative Time to Fill Pools to 1982 Condition
Current Operations	0.9	1.0
Scenarios		
Humpback Chub	0.3	3.0
Common Native Fish	0.8	1.0
Trout	1.4	0.6
Terrestrial Vegetation and Wildlife	1.5	0.6
Combined Recreation	0.9	1.0

Flow in secondary eddies is always of lower velocity than that in primary eddies and return current channels, and typically is lower in sand transport capacity (Table A-5). Measurements show that the highest velocities in the return current channel are typically between 0.2 and 0.4 times the velocity of the nearby main channel flow (Table A-5). Typical mean velocity of the return current is between 1 and 4 ft/s, whereas that of secondary eddies and low-velocity areas is typically less than 1 ft/s, even at flood flows of 40,000 to 50,000 cfs. In almost all recirculation zones, velocities over the reattachment deposit and in the return current channel are high enough to move the fine and medium sand of which the deposits are composed. The transport capacity of recirculation zones is much less than that of the main channel, and that of secondary eddies much less than that of the primary eddy. Sand deposits accumulate where transport capacity is lowest.

At the relatively high flows which inundate separation deposits, sand may be deposited directly from suspension in the low-velocity areas which cover separation deposits (Figure A-3). However, direct

Table A-5. Summary of hydraulic and sediment transport characteristics in the vicinity of recirculation zones (transport rates based on average velocity and depth, with data from Colby 1964, Figure 26). (From Schmidt 1987)

Locations Shown on Figure A-3	Range of Measured Velocity (ft/s)	Velocity Average (ft/s)	Average Depth (ft)	Estimated Range of Fine Sand Transport Rate (tons/day/ft)
Main Channel	5.4 - 25.1	N/A	30 - 60	100 - 10,000
Recirculation Zones:				
Primary Eddy Return Channel	1.2 - 4.0	N/A	5 - 20	1 - 10
Reattachment Point Area (Vicinity of Reattachment Deposits)	0.3 - 2.5	1.5	1 - 4	1 - 10
Secondary Eddy Low-Velocity Area (Vicinity of Separation Deposits)	0.2 - 1.6	1.0	1 - 3	0.1 - 1

observation of sand transport and examination of structures within sand deposits which reveal current directions show that sand is also transported near the bed across the top of the reattachment deposit toward the return current channel and the separation deposit (Schmidt and Graf 1987; Schmidt 1987) (see Figures A-2 and A-3). Although the proportion of sand in separation deposits derived from reattachment deposits is not known, and the mechanisms of this transport is not well understood, it seems clear that some of the sand in separation deposits is derived from that source.

The location and stability of separation deposits are controlled by the debris fan which creates the recirculation zone. Separation deposits typically are not found on the downstream side of debris fans with steep, high slopes, because low-velocity areas or secondary eddies are not present at any discharge. At locations where separation deposits do exist, they are protected from high-velocity downstream flow by the debris fan unless discharge is high enough to inundate the fan. Relatively low, broad debris fans are inundated at lower discharges than high, steep fans. Separation deposits associated with these low fans are more susceptible to erosion than those associated with high fans. (See Schmidt and Graf 1987.)

Recirculation zones change in size and probably in velocity as discharge in the main channel changes. Virtually all reattachment deposits along the Colorado River in Grand Canyon are inundated at discharges of 15,000 cfs, and reattachment deposits are formed at discharges of about 15,000 cfs or greater. As discharge increases, the zone extends in length, and flow velocities within the zone probably increase. These two changes result in shifting patterns of flow and an overall increase in transport capacity of the recirculation zone. Increasing length of the zone, increasing depth of water, and increasing velocity result in a greater area of inundation, and ultimately in scour of the higher parts of reattachment deposits. Most reattachment deposits are entirely inundated by a discharge of about 45,000 cfs.

Sand deposits in recirculation zones change in location and size because of these changes in recirculation zone characteristics. Separation deposits are typically higher in elevation and are inundated by secondary eddies of lower velocity than the primary eddy. Therefore, they are not subjected to potential scour until discharge is high, and at any discharge they are subjected to lower velocities than are reattachment deposits. The change in size of recirculation zones with discharge results in changes in flow pattern which cause loss of sand independent of velocity changes. As primary eddies decrease in size with decreasing discharge, sand deposits which were within recirculation zones at higher discharges become subjected to downstream flow, and sand is lost to the main channel. The susceptibility of separation and reattachment deposits to scour-and-fill and therefore to possible loss is summarized in Table A-6.

Table A-6. Matrix of susceptibility to scour of separation and reattachment deposits for selected flows (Schmidt 1987).

	Separation Deposits				Reattachment Deposits	
	High Fans		Low Fans			
Flows	Narrow Reaches	Wide Reaches	Narrow Reaches	Wide Reaches	Narrow Reaches	Wide Reaches
Powerplant	low	low	medium	low	medium	medium
Floods to 50,000 cfs	medium	low	high	medium	high	medium
Floods above 50,000 cfs	high	medium	high	high	high	high

As sand is moved to adjust to changing flow conditions within a recirculation zone, some transported sand is exchanged between the main channel and the recirculation zone. The rate at which sand and water are exchanged is not known, but evidence suggests that sand is exchanged over a wide range of discharges. (See Schmidt and Graf 1987; and Schmidt 1987.)

Because a model linking main channel and recirculation zone sand transport is not available, it has been assumed that the rate of transfer of sand between main channel and recirculation zone is dependent on the amount of sand being transported in the main channel. Therefore, higher rates of main channel sand transport provide a greater supply of sand to be deposited into the low-velocity parts of recirculation zones where campsites or terrestrial habitats exist.

The important recirculation-zone processes that affect transport and storage of sand in camping beaches are summarized in Table A-7 on a relative discharge scale. Important sediment transport processes in the main channel that affect the amount of sand available for resupply of sand to recirculation zones are also given in that table. If sand is available for transport, then at some discharge below maximum powerplant discharge, sand in some main channel reaches begins to be transported. Pools begin to degrade when flows reach the point at which they can transport the material on the bed. Degradation continues as flows continue to increase. Reattachment deposits, which are exposed at low discharge, are inundated at discharges below powerplant maximum. The rate of exchange of sand between the main channel and recirculation zones is probably low at these lower discharges. As discharge increases, recirculation zones lengthen, scour-and-fill of sand within these zones increases, debris fans begin to be inundated exposing some separation deposits to downstream flow, and sand transport increases. The exchange of sand between the main channel and recirculation zones probably increases. At flood (40,000-50,000 cfs) and higher discharges, recirculation zones begin to disappear as more fans are inundated, and scour-and-fill of separation deposits becomes extensive. It is assumed that the rate of exchange of sand between main channel pools and recirculation zones is highest at high discharges.

When discharge rapidly decreases, many reattachment deposits become exposed, and flow in the return current channels stops. If discharge drops still further, the return current channel may be cut off from the main channel. When there is little or no flow in return current channels but a connection with the main channel is still open, these stagnant areas, or backwaters, are rearing areas for juvenile fish. Backwaters formed in return current channels are the major backwater sites,

Table A-7. Conceptual model of main channel pool and recirculation zone interactions. Information for main channel processes comes from analysis of data from gaging stations (Burkham 1987; Graf and Burkham In preparation), modeling (Randle and Pemberton 1987), and rapid studies (Kieffer 1987). The relative rate of exchange between the main channel pools and recirculation zones is an assumption based on intuitive reasoning. Recirculation zone processes are drawn from Schmidt and Graf (1987) and Schmidt (1987).

Approximate Discharge	Main channel Processes	Sand Exchange Rate	Recirculation Zone Processes	
POWERPLANT 0 cfs			reattachment deposits inundated	Recirculation zones inundated
	sand transport and degradation begin	low	scour-and-fill of reattachment deposits begins	
31,500 cfs				Recirculation zones lengthen
FLOOD RELEASES	significant degradation; sand transport high	moderate	scour-and-fill of reattachment deposits; separation deposits at low debris fans inundated and scour-and-fill begins	
		high		Recirculation zones decrease in number and size because of inundation of debris fans
100,000 cfs	newly deposited debris in rapids may show significant adjustment		separation deposits at high debris fans inundated and scour-and-fill extensive	

although others exist, such as those near the point of flow separation. Mapping and analysis of the occurrence of backwaters show that such areas were created during the study period when discharge decreased rapidly from steady flows of about 28,000 to 6,000 cfs in October 1984 and from steady flows of about 45,000 to 35,000 cfs in June 1985 (Figure A-7).

Processes at Rapids

As noted above, coarse sediment is delivered to the Colorado River primarily by debris flows. This coarse debris increases the size of tributary debris fans and increases river bed elevation at the tributary mouth, constricting the flow of the river. Changes to a fan at the mouth of Crystal Creek (River Mile 98) caused by a major debris flow in 1966 are shown in Figure A-10. Kieffer (1985; 1987b) has developed a conceptual model for evolution of the channel after a debris flow. Before the flow, the river may be constricted to some degree by an old fan (Figure A-11a). The new debris flow may dam flow in the river, forming a "lake" behind the newly emplaced debris (Figure A-11b). River flow begins to erode a channel through the debris when it overtops the dam (Figure A-11c). Small to moderate floods in the river further erode the fan and reduce the constriction by widening the channel and decreasing the slope and elevation of the bed (Figure A-11c, d, and f).

Most rapids have constriction ratios (ratio of channel width at the constriction to channel width upstream of the constriction) of about 0.5 (Kieffer 1985; Schmidt and Graf 1987), suggesting that they have become stable with respect to some flow condition. Widening of the constriction and decrease in bed elevation will take place if velocity in the constriction is high enough to move some of the coarse material which makes up the bed. Widening may continue until the velocity decreases to the point at which flow cannot continue to move coarse debris (Kieffer 1985).

Changes at rapids caused by debris flows change the hydraulic conditions above and below the rapid (Kieffer 1985; Burkham 1987). Constriction of the channel and increase in bed elevation decrease the velocity and increase the water surface elevation for a given flow in the pool upstream of the rapid. The changes result in deposition of sand and gravel in the pool if sediment is in sufficient supply. Burkham (1987) has documented the increase in bed elevation at the USGS gage near Grand Canyon which occurred in response to

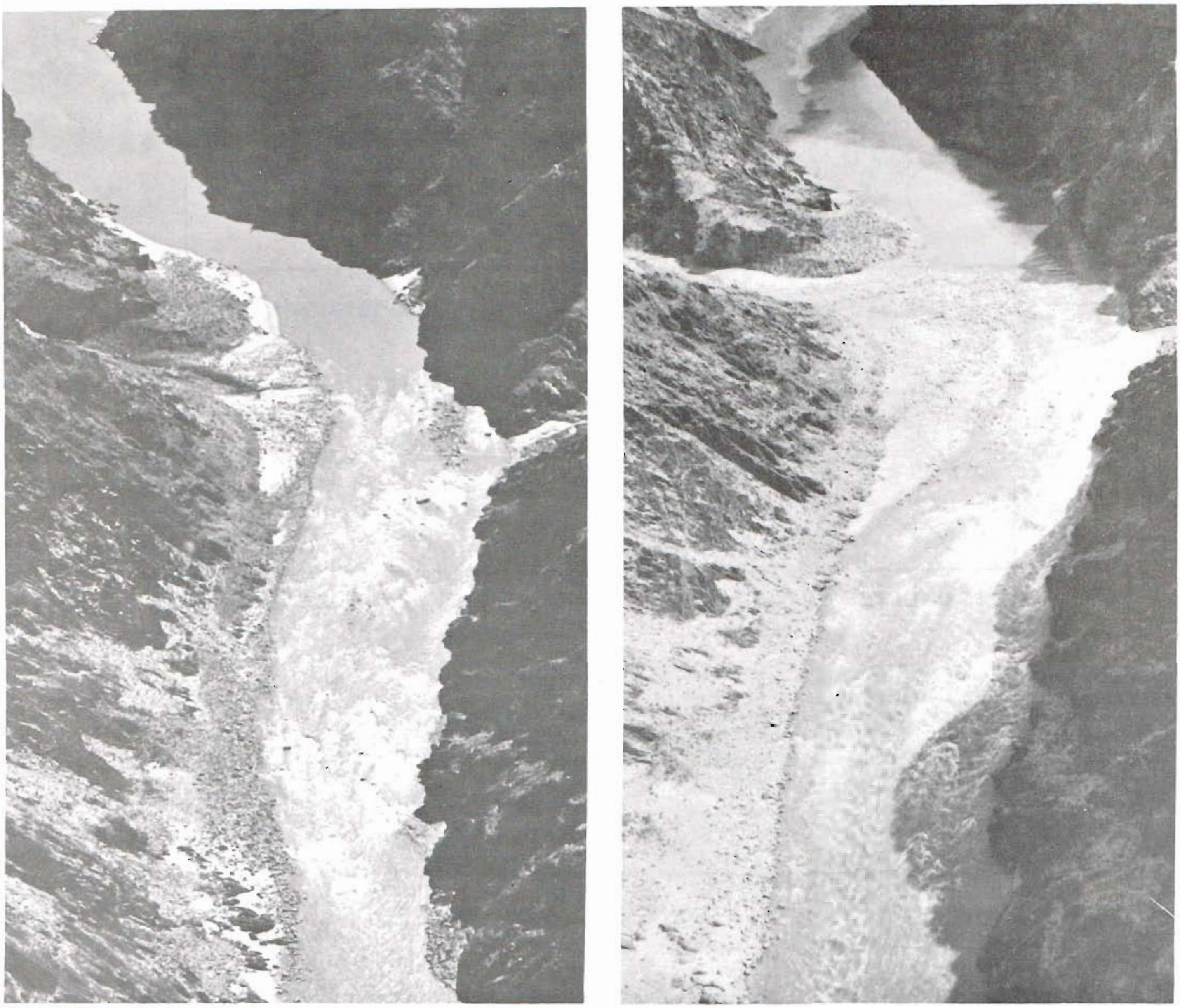


Figure A-10. A debris flow in December 1966 greatly increased the constriction of the channel at Crystal Creek (River Mile 98.1). Left photo by A.E. Turner, Bureau of Reclamation, March 1963 (#P 557 420 8115 N.A.). Discharge 5,000 to 6,000 cfs. Right photo by Mel Davis, Bureau of Reclamation, March 1967. Discharge 16,000 cfs.

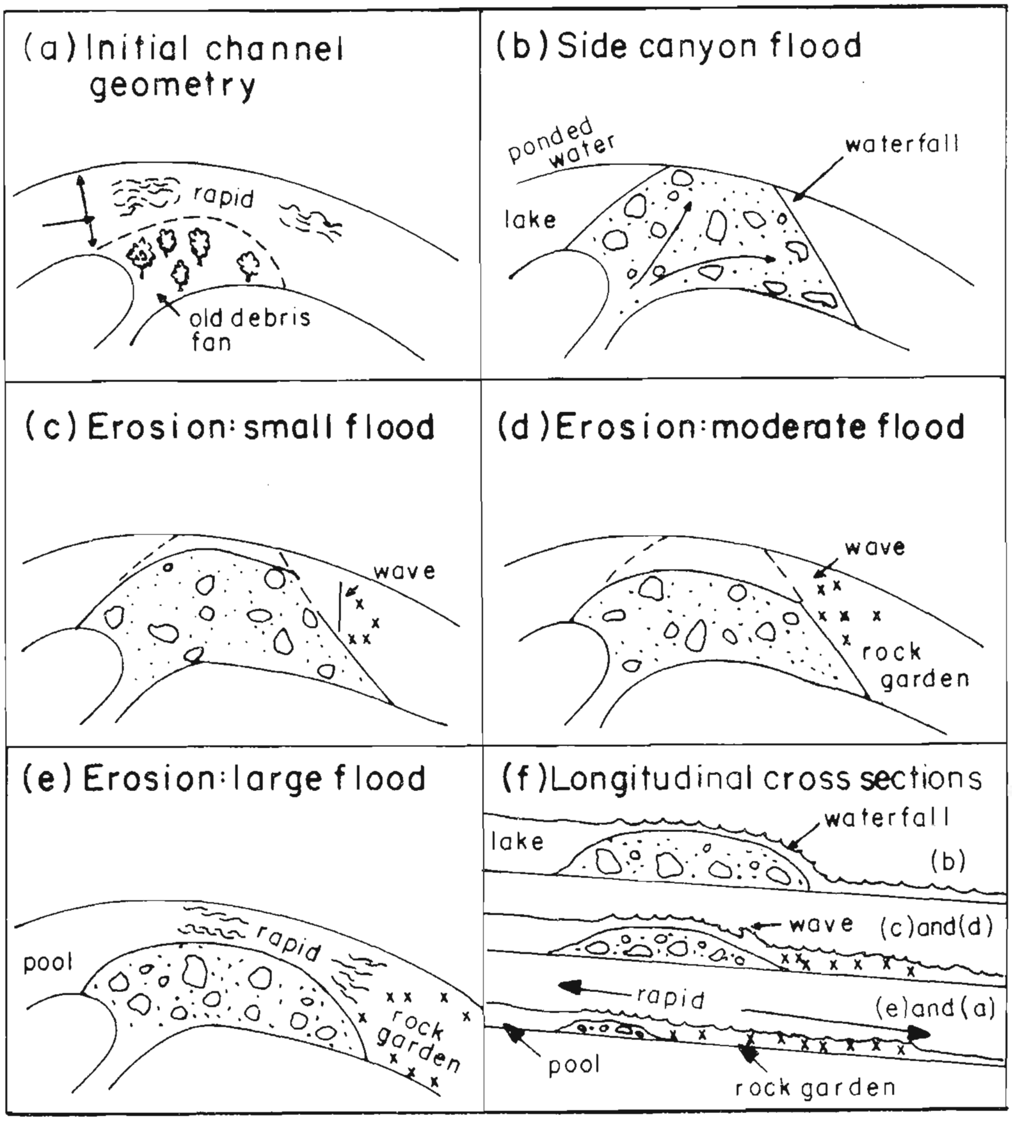


Figure A-11. Channel constrictions caused by debris flows are modified and widened by main channel flows. Rapid condition prior to a debris flow (a). After a debris flow, the river may be dammed (b). Powerplant flows or small floods will erode a small channel through the fan and redistribute rocks (c). Moderate to large floods further reduce the constriction and redistribute rocks downstream of the rapid (d & e). Elevation of the bed and slope through the rapid are decreased as debris is redistributed (f). (After Kieffer 1985) deposition of new debris on the rapid below the gage in 1966 (Figure A-9). New debris flows can be expected to also change the size and shape of recirculation zones adjacent to the rapid, changing the sand transport and storage conditions. Because the magnitude and frequency of debris flows and the movement of newly added debris by river flows are unpredictable, the effects of these changes on sand transport and storage cannot be determined at the present time.

Waves in rapids are caused by large obstacles on the bed (such as rocks), by contraction and expansion of the flow as it passes through the constriction, and by irregularities in the shoreline. Wave characteristics are different at different discharges (Kieffer 1987b). Difficulty of navigation through rapids depends on wave characteristics, flow velocity, and distribution of rocks in the rapid. Navigation safety is dependent on complex and variable hydraulic and bed conditions as well as on skill of the white-water boater. The limited state of present knowledge prohibits the development of a model which could predict boating safety at a given flow.

Response of Sediment to Floods

Floods degrade main channel pools. STAB model computations indicate that degradation of channel pools occurred as a result of the exceptionally high flood releases of 1983 (up to 97,200 cfs) and that degradation continued during the flood releases of 1984-1986 (40,000-50,000 cfs). According to the STAB model, the combined effect of 1983-1985 flood releases was to remove about 15.6 mt of sand from the channel in the reach between the USGS gages at Lees Ferry and near Grand Canyon. Because the relationships used in the STAB model between sand transport and discharge at the USGS gaging station near Grand Canyon and gaging stations farther downstream are the same, the STAB model results showed no significant channel degradation downstream of the gage near Grand Canyon during the 1983-1985 flood flows. (See Randle and Pemberton 1987.) However, bed elevation changes at a gaging station above National Canyon (River Mile 165) (Graf and Burkham In preparation) shows that the bed did degrade locally as the 1983 flood was receding.

Floods cause long-term loss of camping beaches. Analysis of surveys of camping beaches and of aerial photographs taken in 1973 and 1984 indicate that as a result of flood releases of 1983-1984, narrow reaches and the wide reach just downstream from Lees Ferry experienced a net loss of sand from recirculation zones. For these two flood years, separation deposits were more stable than reattachment deposits, and campsites were more stable than recirculation zone deposits as a whole. Area of some deposits significantly decreased in narrow reaches. Although some campsites at separation deposits showed significant vertical aggradation as a result of these floods, much of the gain was obliterated after a short time of lower flows. (See Schmidt and Graf 1987.)

Floods occurring when pools are at a low bed elevation are projected to result in more extensive loss of sand-dependent resources than occurred during the period 1983-84, when high flows were preceded by conditions of relatively high bed elevation in pools. When floods occur when bed elevation in pools is already low, little sand is delivered into recirculation zones from the main channel and sand may be lost from those zones. If floods are necessary for other purposes, their impact on campsite beaches is expected to be less under high bed elevation conditions in main channel pools.

As stated previously, sand transport in the main channel should be higher during floods occurring when main channel pools are at a high bed elevation. However, high discharges occurring when bed elevation is high may not be beneficial to rebuilding campsite beaches, even though some sand deposits did aggrade in 1983. As discussed above, the high flows of 1983-84 caused loss of sand from camping beaches in narrow reaches where campsite availability is already limited. Where sand deposits aggraded, they were typically rapidly degraded during subsequent lower flows. Even though separation deposits were more stable than reattachment deposits in the floods of 1983-1984, the loss of sand from reattachment deposits suffered in those floods may eventually result in loss from separation deposits. This is because some of the sand in separation deposits is apparently derived from the associated reattachment deposit. Therefore, depletion of sand from reattachment deposits may even- tually affect separation deposits, and camping beaches may be lost at a greater rate during future floods than in 1983-84. The processes involved in sand transport from reattachment to separation deposits are not understood well enough for us to estimate the rate at which this loss would occur under given flow conditions.

Marsh vegetation became established in wide reaches of Grand Canyon after flow regulation began in 1963. Marshes developed where large reattachment deposits became overgrown by cattails and other marsh vegetation. Preliminary analysis of former marshes indicates floods of 1983-1986 scoured the marsh vegetation and probably eroded several vertical feet of sand from these reattachment deposits. (See Brown and Schmidt In Preparation.)

Because loss of some campsites and other sand-dependent resources was caused by the floods of 1983-1984, which occurred after about 20 years of powerplant releases, additional floods occurring once in 20 years or more frequently are projected to result in the gradual loss of sand-dependent resources over the long-term. Loss will be greatest in narrow reaches throughout Grand Canyon and in all reaches upstream of the Little Colorado River. The projection is made assuming that average annual sand delivery by tributaries will not change significantly with time. An exceptionally large delivery of sand, such as would result from a very large runoff event in the Little Colorado or Paria Rivers, could refill main channel pools in less time than estimated under conditions of average annual sand delivery and could result in temporary rebuilding of camping beaches and other sand deposits. However, a significant, sustained increase in average annual sand delivery would probably be required to eliminate or reverse the projected trend toward loss of sand over the long-term. Magnitude and duration of floods also affect the rate of sand loss, but our present knowledge is not sufficient to define the relative importance of the factors to sand loss.

<u>The response of channel margin deposits is uncertain.</u> Channel margin deposits typically line the channel for long distances in wide reaches of the canyon and are often heavily vegetated. Preliminary analysis indicates that many channel margin deposits may be created in small recirculation zones, but that their behavior and response to high flows is more like main channel pools than recirculation zone deposits (Schmidt and Graf 1987). The area of sand exposed at low discharge increased at many sites in the reach from River Mile 122 to River Mile 160 between 1973 and 1984 (Schmidt and Graf 1987, Table 11). Vertical aggradation of channel margin deposits was reported by Beus, Carothers, and Avery (1985). However, many of these deposits were eroded by high flows in 1983-84. The mixed results of past monitoring of a

relatively few deposits prevents us from making definitive predictions about future behavior of channel margin deposits.

<u>Flood flows may be required to maintain rapids at their present condition.</u> A debris flow in Crystal Creek (River Mile 98) in December 1966 constricted the river and formed what is now one of the largest rapids in Grand Canyon. Between 1966 and 1983, the constriction widened to a ratio of about 0.25 (Kieffer 1985). During that time, river flows were within the range of the powerplant for all but a few weeks in 1980, when peak discharge reached 44,800 cfs at Lees Ferry (U.S. Geological Survey b, issued annually). The record post-dam flood of 1983 (Figure A-6), with a peak discharge of 97,200 cfs at Lees Ferry, further widened the constriction to a ratio of about 0.4 (Kieffer 1985). Kieffer (1985) has estimated that a discharge of about 400,000 cfs would be required to further widen this constriction to a ratio of about 0.5.

The rainstorm that triggered the debris flow in Crystal Creek also caused a debris flow in Bright Angel Creek. The rapid and debris fan at Bright Angel Creek control the relationship between stage and discharge at the USGS gage near Grand Canyon. Burkham (1987) has used changes with time in that relationship to get information on changes in the rapid and debris fan. He has shown that some of the newly deposited debris was removed in the first few years after the flow, when river flows remained within the range of powerplant releases. However, it took the high flows of 1983 to return the rapid to its pre-1966 condition.

We conclude from the evidence available that although substantial reworking of newly emplaced debris can take place at flows within the range of the powerplant, it probably takes much higher flows to return the constriction to a ratio of 0.5, the condition of pre-dam stability. We cannot say for certain whether flows approaching maximum pre-dam flows (300,000-400,000 cfs) or lower, more frequent flows (for example, the average annual pre-dam peak flow of about 94,000 cfs) are required to return the constriction to the 0.5 constriction ratio. Because navigation safety depends on many factors other than channel constriction, we are unsure at this time of the importance of this conclusion to future safety.

Response of Sand Deposits to Fluctuating Flows

Sand transport in the main channel is slightly higher under fluctuating flows than under steady flows. Estimates of transport with the STARS model indicate that for the same annual flow volume, the amount of sand transported by fluctuating flows is slightly larger than that transported by steady flows within the range of powerplant discharges. For an annual release volume of 8.2 maf, the model resulted in 12 percent less sand stored on the main channel bed between Lees Ferry and the Little Colorado River for steady relases than for maximum daily fluctuations (Randle and Pemberton 1987). Sand transport measured at the gaging stations during steady flow in 1983 and fluctuating flows in 1985-1986 could not be directly compared because of the large difference in volume of flow for the two periods.

Onset of fluctuating flows may cause loss of camping beaches for a short period of time. Repeated topographic surveys made during a special period of fluctuating flow between October 1985 and January 1986 (Figure A-7) demonstrate that rapid loss of sand from camping beaches occurs throughout Grand Canyon when fluctuating flows follow flood flows. The response of the separation deposit at Eighteen Mile Wash (Figure A-12) to flows is indicative of response at other studied sites. Surveys of that deposit from 1975 to 1986 show that the 1983 high flows caused some degradation of the top of the deposit but also caused aggradation of the deposit toward the river. Subsequent floods in 1984 and 1985 caused additional aggradation on the streamward side of the deposit. Surveys of May 1985 and October 1985 show that sand was lost from the deposit during the periods of lower, relatively steady flows that followed each of those floods (Schmidt and Graf 1987) (see Figure A-7 for flows during these periods). Surveys of August 1985 and January 1986 (Figure A-12) bracketed the special fluctuating flow study period and show that sand was rapidly lost from the streamward side of the deposit in response to those fluctuating flows. Although the amount of loss measured during the fluctuating flow study period was not as great as losses caused by lower, steady flows, the time of exposure of deposits to fluctuating flow was much shorter, and the rate of loss was greater.

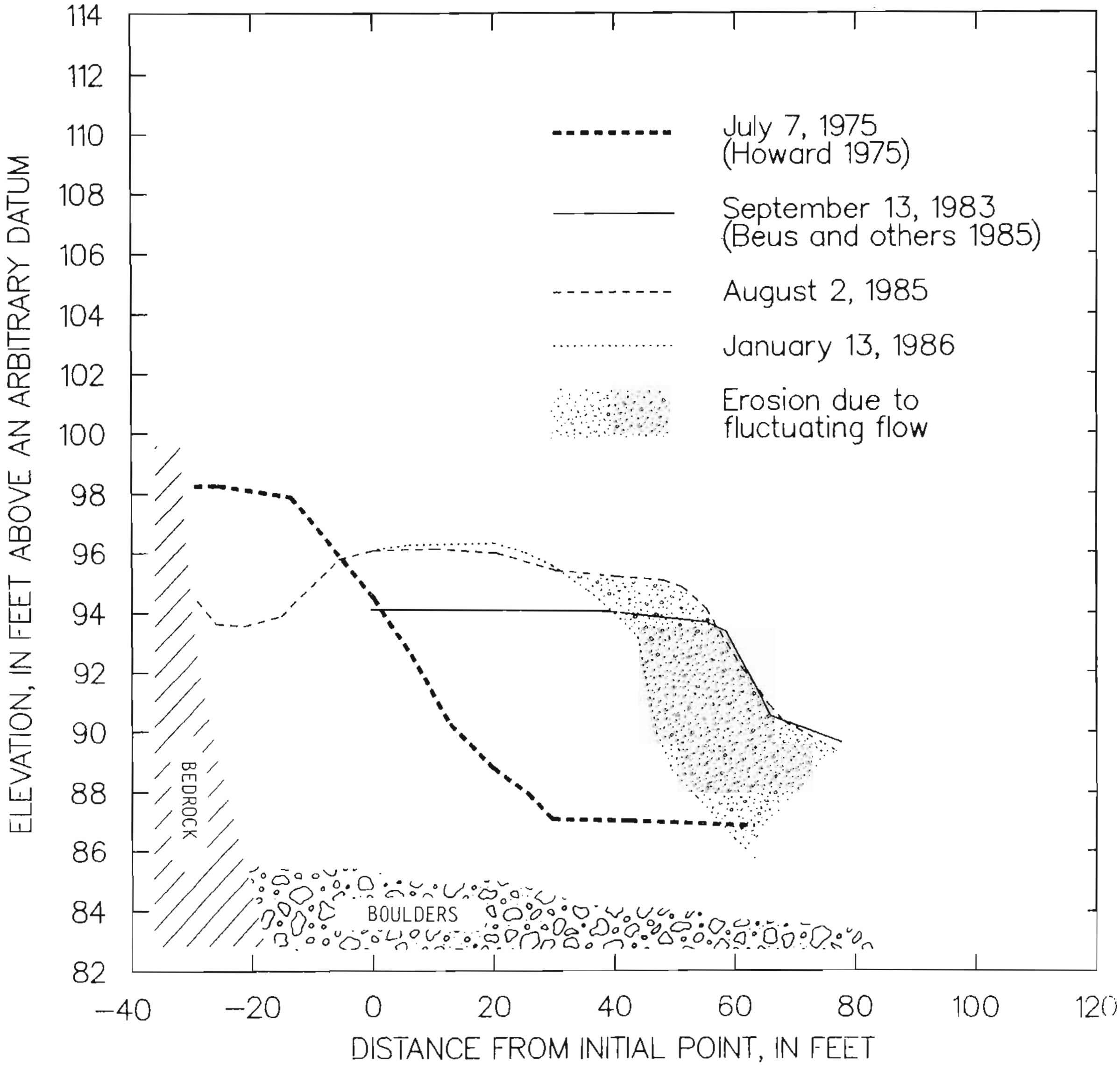
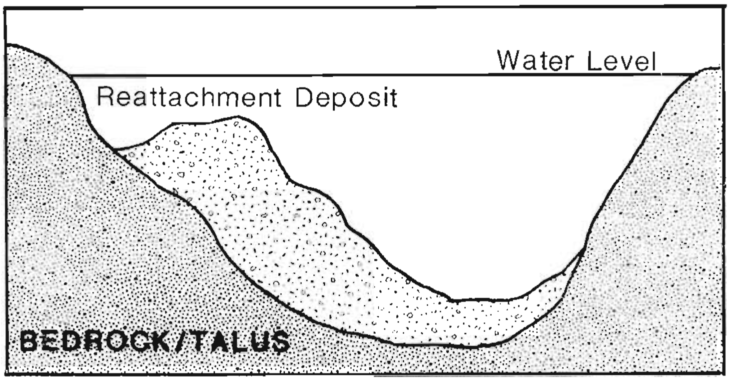


Figure A-12. Topographic changes along a single profile line bisecting a separation deposit at Eighteen Mile Wash (River Mile 18) from 1975 to 1986. (After Schmidt and Graf 1987, Figure 27)

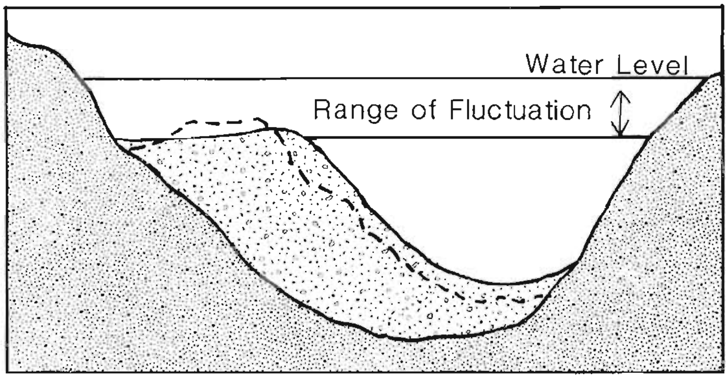
The surveys presented in Figure A-12 and documented by Schmidt and Graf (1987) suggest that steady or fluctuating flows within the powerplant range would eventually erode the deposit to a position near that it occupied in 1975. This stable profile would probably be reached sooner if flows fluctuated during the adjustment period. The position of the stable profile probably depends on a frequently occurring peak discharge (Schmidt and Graf 1987). Because fluctuating flows have a higher peak discharge than steady flows of the same volume, the sand deposits which reached a stable condition under fluctuating flows would have smaller areas than those which reached a stable condition under steady flows of the same volume. For example, the difference in maximum water surface elevation between flows fluctuating to 31,500 cfs and steady flows of 12,000 cfs is over 7 ft in narrow reaches. Camping beaches stabilized to the lower water surface elevation would have significantly more area than those stabilized to the high elevation.

Losses similar to those resulting from fluctuating flow at Eighteen Mile Wash were measured throughout Grand Canyon during the same time period, although the amount of loss was greater in narrow reaches of the river. Measurements during the special fluctuating flow study period also showed that loss was most extensive at locations where significant aggradation had resulted from the 1983 high flows. (See Schmidt and Graf 1987.) These data suggest that many deposits created by high discharges are unstable when exposed to lower steady flows or to fluctuating flows. Surveys made in the late 1970s and early 1980s (Howard and Dolan 1981) showed that campsite beaches had reached equilibrium with respect to the range of daily fluctuations characteristic of that period. Therefore, these results suggest that after a period of loss, campsite beaches adjust their profiles to the range of fluctuations characteristic of normal operations and that the extensive loss measured during the special fluctuating flow study period was not indicative of long-term trends.

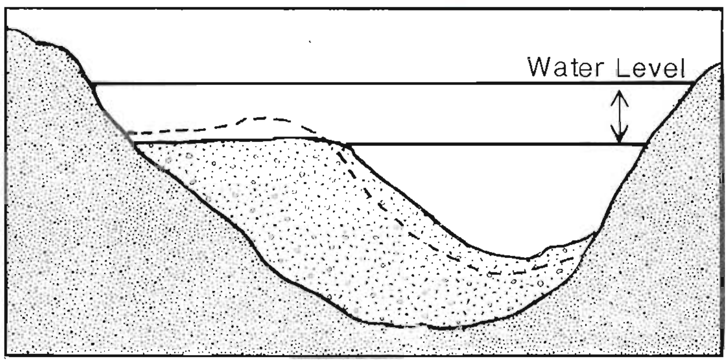
<u>Fluctuating flows may decrease the depth and number of backwaters.</u> Bathymetric maps of recirculation zones and adjacent main channel pools and topographic maps made from surveys of exposed deposits just before and near the end of the fluctuating flow study period of 1985-1986 (Schmidt and Graf 1987) show that some reattachment deposits may respond to fluctuating flows as shown in Figure A-13. Steady flows which inundate



A. High Steady Flow



B. Initial Response to Fluctuating Flow



C. Long-term Response to Fluctuating Flow

Figure A-13. Response of main channel and recirculation zone bed to fluctuating flows. Steady flows which submerge a reattachment deposit create a return flow channel (A), fluctuating flows may move sand from the recirculating zone into the main channel (B), and obliterate the return flow channel (B & C). (After Schmidt 1987) the deposit create high reattachment deposits and deep return current channels (Figure A-13a). Fluctuating flows gradually flatten the reattachment deposit and fill in the return current channel (Figure A-13b and c). Sand removed from the upper surface of the deposit is deposited on the slope of the recirculation zone deposits which borders the main channel, where it may be exposed to the downstream flow of the main channel. The reduction in size of the return current channel reduces the area of backwaters available for fish, and may reduce the range of flows at which the channel is useful to fish.

SECTION III: IMPACTS OF CURRENT OPERATIONS

Current Operations Defined

Impacts of current operations (and each of five modified operations in Section IV) were evaluated by assuming a series of low- and high-water years that produce approximately the average annual runoff. Dam releases for the low-water year are assumed to be similar to that in 1982, when annual releases totalled 8.31 maf. Water year 1986, with a total annual release of 16.6 maf, was used as the basis of the high-water year operation. It was assumed that three years of low releases would occur for every one year of high release. The GCES Final Report, Figure VI-1 gives daily flows for water years 1982 and 1986, and Appendix D gives the basis for this definition of current operations.

Floods

Floods like those of 1986, which are expected to occur one year in four under current operations of Glen Canyon Dam, probably will result in long-term loss of sand from recirculation zones, primarily in narrow reaches of the river and in the reach from Lees Ferry to the Little Colorado River. Sand loss will result in loss of some sand-dependent resources--camping beaches, substrate for vegetation, and backwaters. Rate of loss will be dependent on the amount of sand delivered by tributaries and will decrease downstream as more tributaries join the river.

Estimates made with the STAB model suggest that sand storage in main channel pools will increase under current operations and average annual tributary delivery of sand. This will gradually raise the elevation of the channel bed. Aggradation is predicted because the degradation associated with the short periods of flood releases which occur every fourth year is more than balanced by the aggradation during the low-release years. STAB model computations for the reach from Lees Ferry to the Little Colorado River yielded an estimate of about 20 years for aggradation of the channel bed under current operations.

During the flood release periods which occur every fourth year, large parts of camping beaches will be inundated and the sand deposits which form them subjected to scour-and-fill. When floods occur during the period of main channel pool aggradation, the amount of sand brought into the recirculation zone will probably be insufficient to replenish the entire amount of scoured sand, and degradation will result. Because the rate of sand transport in the main channel at a given discharge is greater when main channel pools are at a high elevation, loss of sand from recirculation zones is projected to decrease over the next 10 to 20 years as pools begin to reach a high elevation, but the rate of decrease depends on the amount of tributary sand delivery. The gradual loss of sand from recirculation zones will decrease the sandy areas on which marsh vegetation could become established. Backwaters also will decrease in response to the loss of sand. Under current operations, the possibility exists that debris flows in tributaries will add material to riffles or rapids that cannot be moved. Flood releases one year in four will move more debris than powerplant flows, but frequent flood releases of 40,000-50,000 cfs probably are incapable of removing all newly added debris, and rapids may become more difficult to navigate.

Fluctuating Flows

Evidence summarized in previous sections supports the conclusion that sand deposits respond rapidly to the onset of fluctuating flow but reach a stable condition within a period of six months to a few years. The stable condition reached for a given range of fluctuations will depend primarily on the peak flow of the fluctuations, so that the higher the peak, the smaller the area of sand remaining for campsites or vegetation.

Repeated surveys of recirculation zones made during fluctuating flows in the period October 1985-January 1986 suggest that fluctuating flows decrease topographic relief of sand deposits within the zones and reduce the number and area of backwaters.

SECTION IV: IMPACTS OF MODIFIED OPERATIONS

Rating System for Evaluating Impacts

Five flow scenarios to protect or enhance biological or recreational resources were developed by GCES researchers, and are presented in Appendices B and C along with the evidence and reasoning leading to their development. Each of the five scenarios includes three years of low releases (about 8 maf) and one year of high releases (about 16 maf). A seven point rating system is used in this appendix to summarize the impacts of the scenarios on main channel pool sand storage, camping beaches in narrow and wide reaches, substrate for vegetation, backwaters, and rapids. This system is used only as a means to illustrate relative impacts of the five scenarios, and is not intended to imply value judgements on the part of the researchers. For each scenario, impacts were evaluated relative to the impacts of current operations.

The basis for considering an impact positive or negative was different for the different resources. For main channel pool sand storage, the impact of a scenario was judged to be positive if the scenario was believed to result in a greater rate of sand storage than do current operations. The impact on camping beaches and substrate for vegetation was considered positive if the area of sand deposits available for camping and establishment of vegetation would be greater under the scenario than under current operations. Possible loss of area available for camping because of establishment of dense vegetation was not considered in this analysis. The impact of a scenario on backwaters was considered positive if the scenario was thought to result in a larger number of backwaters available than under current operations.

The impact of a scenario on rapids was considered positive if it was determined to result in constrictions at rapids which would be no smaller than those projected for current operations. Smaller constrictions may make rapids more difficult to navigate and more unsafe. Smaller constrictions caused by buildup of debris from tributary flows increase the area available for sand storage in the main channel and in recirculation zones and change the hydraulics and sand transport capacity of the river. The long-term effect of these changes on beaches is difficult to determine with the present state of knowledge. Although these indirect effects of changes in rapids on beaches may be significant, they have not been considered in this analysis.

Releases to Minimize Loss of Camping Beaches and Vegetation Substrate

On the basis of our current understanding of sand-transport processes, we find that Glen Canyon Dam operations could be modified to maximize area of sand available for camping and establishment of vegetation and to minimize long-term loss of camping beaches. This could be done by releasing the annual flow volume as nearly constant flows. For the low- and high-water years used for comparison, this would result in steady discharges of about 12,000 and 23,000 cfs, respectively. This scheme would eliminate the floods which occur frequently under current operations and which cause scour-and-fill of recirculation zone sand deposits and subject them to possible loss. Fluctuating flows which cause short-term loss and daily inundation of significant parts of many deposits, and which may reduce the number of backwaters, would also be eliminated.

Because floods typical of current operations would be eliminated, camping beaches and substrate would probably become stable above the elevation of the water surface during the high-flow year. Because this discharge is lower than the peak of fluctuations under current operations, this would result in more area available for camping and vegetation than under current operation. In years of high-water release, area available for camping would be less than that in low-release years, but minimal loss of vegetated areas would occur.

Under this scenario, discharge would change only between low- and high-runoff years, and sand would be subject to scour-and-fill only when flows were changed. Main channel pools degraded by the 1983-86 floods would be filled in a few years if tributary sand delivery were average or above average. STAB model computations suggest that pools may reach a stable, high elevation in about one third the time of current operations (Table A-8).

Steady flows in the range of 12,000-23,000 cfs would inundate recirculation zones and form high reattachment deposits and deep, well-developed return current channels. However, these would probably not be available as backwaters because most reattachment deposits would be submerged at all times, and flow velocity in return flow channels would be too high to be attractive to fish.

Elimination of floods typical of current operations may also result in an increase in number of rapids and smaller constrictions for some existing rapids because of buildup of debris from tributary flows.

Releases to Benefit Humpback Chub

The scenario developed in Appendix B to benefit humpback chub includes steady flows at maximum powerplant capacity for May and June in both the high-water year and the low-water year. The remaining months are at constant steady discharge. The rate of main channel pool sand storage for this scenario would be very low because of the period of steady high flows each year. STAB model estimates suggest that under this operation it would take about three times as long for main channel pools to aggrade to a stable, high level as it would under current operations (Table A-8). Low pool bed elevations and the high, steady flows each year would yield a higher chance of loss of camping beaches and substrate under this scenario than under current operations.

Releases to Benefit Common Native Fish

The scenario developed in Appendix B which benefits common native fish has very low releases (5,000 cfs) in the months of June, July, and August for both the low-water and high-water years, and remaining months have a constant, moderately high discharge. Sand storage for this scenario would be relatively low because of the moderately high flows for much of the year. The STAB model computations suggest that this scenario would be about the same as current operations in the time required for main channel pools to reach a stable, high elevation (Table A-8). Elimination of floods typical of current operations would permit beaches and substrate to stabilize at a lower elevation than under current operations, resulting in more area available for camping and vegetation than is available under current operations.

Releases to Benefit Trout

Except for three two-week periods of fluctuating flows each year, the scenario developed in Appendix B to benefit trout is identical with the one developed for camping beaches and vegetation substrate. These short periods of fluctuations are expected to have only a slight impact on sand deposits. The period of fluctuating flow in September may move some tributary sediment into the lower elevation areas of recirculation zones (Table A-8).

Table A-8. Five scenarios rated* for impact on resources related to sediment.

RESOURCE	SCENARIOS: Beaches/ Habitat/ Wildlife	Humpback Chub	Common Native Fish	Trout	Recreation
Main Channel Sand Storage	3	-3	0	3	0
Camping Beaches					
Narrow Reaches	2	-1	1	2	1
Wide Reaches	2	0	0	2	2
Substrate for Vegetation	2	-1	1	2	2
Backwaters	-2	-2	-1	-2	1
Rapids	-1	-1	-1	-1	-1

* Rating: Positive Relative Impact: 3 = high, 2 = medium, 1 = low; No Difference: 0; Negative Relative Impact: -1 = low, -2 = medium, -3 = high

Releases to Benefit Recreation

The scenario developed to benefit recreation has the greatest variation in flow during the year of any of the scenarios developed and evaluated. Flows are about 30,000 cfs during the white-water boating season (May through September) and about 10,000 cfs during the fishing season. The change in flow level twice each year would probably result in unstable sand deposits. However, elimination of floods typical of current operations would protect from loss camping beaches and substrate at elevations corresponding to flows above powerplant releases. Computations with the STAB model suggest that rate of sand storage would be about the same as for current operations (Table A-8).

Releases to Mimic Pre-Dam Flows

Although more natural flows may be desirable to some recreationists and could be expected to result in vegetation more like that of the pre-dam era, releases which mimic flows typical of the period before the dam would result in rapid loss of camping beaches and substrate. The extremely high flows during the spring and early summer months, combined with no increase in sand delivery, would scour sand from main channel pools and cause severe erosion of beaches and other sand-dependent resources. New debris deposited on rapids would be adjusted more rapidly and to a greater degree than under current operations. However, it may not be possible to release flows high enough to maintain constrictions at the pre-dam condition.

Increased Powerplant Releases Due to the Uprate and Rewind Program

The change in water level which corresponds to a change in flow from 31,500 to 33,100 cfs is greatest in narrow reaches, but data from USGS gaging stations and temporary water level measurement sites at other locations show that the maximum water level change would only be about 5 inches. This small increase would probably not cause significant loss of camping beaches or other sand-dependent resources. However, although 31,500 cfs was the stated upper limit of releases before the recent rewind and uprating of the generators at the powerplant, discharges between 27,500 and 31,500 cfs were infrequent in the period from 1963 to 1982. Sand-dependent resources were probably stabilized to a flow which is lower than 31,500 cfs. Without knowledge of how the new capacity will be used, it is not possible to determine the effect of the change in capacity on sediment-dependent resources at the present time. However, if discharges are frequently near the new powerplant capacity of 33,100 cfs, then sand deposits would stabilize to that higher discharge. Differences in water surface elevation corresponding to the difference between 27,500 and 33,100 cfs are about 1.5 ft for narrow reaches and about 1 ft for wide reaches. This greater difference in water surface elevation could result in significant loss of area of camping beaches, substrate, and backwaters, particularly in narrow reaches where the difference is greatest.

SECTION V: DATA GAPS AND UNCERTAINTIES

Conclusions presented in this report are based upon data we had available and analyses which were completed within the time frame of the studies. They include uncertainites in estimates given and gaps in our knowledge. However, we believe that these uncertainties and gaps do not affect the main conclusions of this report regarding floods and fluctuating flow.

Data related to sediment transport were collected during the period 1983-1986. This was a period of unusually high releases in relation to the history of operations of Glen Canyon Dam during the period 1963-1982. Releases during the period of data collection were not only higher, but they were steadier than those previously experienced. This period did, however, present the opportunity to study the effects of flood releases which may be typical of operations in the future and which have been found to be the most important factor affecting the long-term condition of all sediment-dependent resources.

Data collection did not begin until the recession of the exceptionally high flood of 1983. Therefore, few data are available on the nature of sediment transport and storage changes during the critical time of rising flow. Much change in sand deposits probably had already occurred before data collection began. The period of direct observation of response of sand to fluctuating flow was very short (16 weeks) and followed three major flood periods.

Only limited data were collected concerning camping beaches and vegetation substrate before 1985. Limited data are available to describe behavior of these deposits during passage of a flood. The existence of previous surveys and aerial photography and the examination of internal structures of sand deposits to reconstruct depositional history partially compensated for the lack of data during the study period.

Specific gaps and uncertainties in data are given below.

Amount of Sand Stored

No direct measurements of the thickness of sand in recirculation zones were made, but estimates were arrived at by projecting the bedrock surface under sand between known points. The amount of sand stored in the main channel bed was estimated using thickness of sand measured in cores taken before this study and from knowledge of the depth of scour at gaged pools. Storage changes with time determined from repeated discharge measurements at the gaging station sections may not be representative of those elsewhere in the river. Attempts to determine long-term storage changes in the main channel by comparison of repeated depth-sounder records have not been successful because depth variations caused by location error are of the same order of magnitude as changes in the bed (Rathburn In preparation).

An unsuccessful attempt was made to estimate outflow from Grand Canyon by examining the deposits in Lake Mead. Seismic reflection techniques used were unable to identify changes in deposits with depth which could be related to deposition since dam construction.

Sand Transport

Sediment samples collected during this study represent the largest set of data available for determining how sand transport in Grand Canyon varies with flow (Pemberton 1987). Relationships between sand transport and discharge determined by traditional methods have very high standard errors. Variability in transport relationships is caused by a number of factors, including sampling error, changes in bed elevation, tributary supply of sand, bed materials, and channel hydraulics. The short sampling time limited the range of conditions sampled and therefore limited our ability to isolate the effects of changes in controlling factors. (See Graf and Burkham In preparation; and Pemberton 1987.)

Predictive Models

Uncertainty in the results of the two different types of models used in this report fall into two broad categories--data used in the model and the model itself. The uncertainty in sand transport relationships used are described in the previous section. Bed material size distribution used in the STARS model affects results significantly (Randle and Pemberton 1987). Although bed material was poorly known, reasonable verification was possible when the model was used for periods when samples were available. One hundred ninty-nine cross sections were surveyed with an echo depth sounder to define the geometry of the channel for modeling. Additional interpolated sections needed to reproduce the measured water surface profile were at riffles and rapids where sand storage is not significant.

The STARS model (Randle and Pemberton 1987) is a one dimensional, steady flow model, which does not model supercritical flow. Recirculation zones cannot be simulated with this model, and rapid changes in discharge must be simulated as step increases or decreases between steady discharges. The model was selected for use in the studies because no other model is currently feasible which can simulate the actual physical processes as they exist in Grand Canyon. The model was an important means of projecting results to flows other than those studied, such as modified operational scenarios, and to time periods longer than the study period. A flow routing model recalibrated with data from the study period (Lazenby 1987) underestimates peak discharge by about 5 percent during fluctuating flow and overestimates the low discharge by 5 to 10 percent. As this model was used in sand transport modeling, the error in flow routing contributes to the uncertainty in model results.

Sand Exchange

Conclusions concerning the loss or gain of sand in recirculation zones are based on a data set of repeated surveys and on qualitative observations over a limited time period and limited flow conditions.

In developing the conceptual model of sand storage and transport presented in this report, we have assumed that a link exists between sand stored on the bed of the main channel pools and that stored in recirculation zones. Although little direct evidence of transfer between these two groups is available, several lines of indirect evidence support this assumption. Bathymetric surveys show movement from recirculation zones to the main channel bed in at least one location (Schmidt and Graf 1987). Also, in 1984 when the main channel bed was scoured to a low elevation and was presumably coarser than when it is at a high elevation (Burkham 1987) a significant portion of the bed was fine- and medium-grained sand like that which forms separation and reattachment deposits (Pemberton 1987 and Schmidt and Graf 1987). Therefore, main channel flows are not always capable of transporting sand of these sizes in suspension and does serve as a storage area. In addition, suspended sand concentration in the main channel tends to be lower when the main channel bed is at a low elevation than when it is at a high elevation (Graf and Burkham In preparation). Tributary flows have been observed to result in increase in bed elevation at gaging stations, and material deposited from these flows contains a significant proportion of fine- and medium-grained sand (Graf and Burkham In preparation).

The alternative hypothesis--that sand in recirculation zones is derived directly from tributary flows or other recirculation zones without ever having been on the main channel bed--is possible. If we had assumed that this alternative hypothesis was true, our primary conclusions that flood flows erode camping beaches and that beaches will stabilize to fluctuating flows would not have changed. Those conclusions are based primarily on direct observation of beach response to floods and fluctuating flows.

Sand Delivery

The short period of sediment sampling on gaged tributaries and the large variability in delivery from year to year introduce a large uncertainty in the average values used in this study.

Variations in tributary floodplain storage could lead to significant variations with time in sediment delivery to the Colorado River from the Paria and Little Colorado Rivers. To better estimate future sediment delivery, these variations with time should be considered.

Debris Flows

Debris flows and hyperconcentrated flows are believed to be the dominant mechanism of transport of coarse and fine sediment from ungaged tributaries. However, only about 10 percent of ungaged tributaries were examined in this study. No general model for magnitude and frequency of debris flows was attempted from the limited data set.

SECTION VI: MONITORING AND RESEARCH NEEDS

Conclusions presented in this report concern long-term projections of response of sediment-dependent resources to flows. Periodic monitoring is required to confirm or refine these projections. Monitoring should become an integral part of dam operations. Continued monitoring should be supplemented by research directed at filling the gaps in our present understanding of the response of resources to flow. The monitoring and research program outlined below is designed to reduce uncertainties in estimates and improve our ability to make long-term projections.

Monitoring

The goal of the proposed monitoring program in the main channel and tributaries would be to provide the data base needed to more accurately determine the amount of sand being gained or lost from Grand Canyon and reaches of interest within Grand Canyon, and to better project long-term trends in that loss or gain. The program should include studies to:

- Collect and evaluate sediment data at the four main-channel gaging stations downstream of the Paria River. Evaluate data and reassess the monitoring program every few years.

- Measure discharge at gaging stations as frequently as necessary to monitor bed changes and maintain a stage-discharge rating.

- Document changes to main channel control sections (rapids and riffles) using repeated aerial photography. Repeat hydraulic mapping if significant changes occur.

- Monitor changes in bed elevation at places other than gaged sections using repeated surveys at cross sections, repeated bathymetric mapping of short reaches, or a combination of the two methods. Repeat every few years or after significant flows. Data collected at gaging stations gives reliable information on bed changes that permits the separation of short-term variations from longer-term trends. However, processes at gaging stations may not be representative of processes in the entire channel.

- Develop a reliable base map for future work. The lack of a universally accepted base map led to difficulties in documenting field observations and in integration of results from various studies. The 7 1/2 minute USGS topographic quadrangle maps under preparation could be a base for this map. Uncertainty in location of particular beaches or study sites is as much as one-half mile without such a base map.

- Take low-flow aerial photographs of the river corridor periodically. Annual photographs would be useful for monitoring changes in channel controls, debris flow occurrence, vegetation changes, and changes in sand deposits in recirculation zones.

- Periodically rephotograph from selected historical oblique ground photograph sites.

- Establish and replicate topographic surveys of recirculation zones exposed at low discharges. This should be done every year, or after significant flows (e.g., after the recession from floods). Zones selected for survey should be determined on the basis of significant formative and sediment supply characteristics.

- Collect sediment and flow data on gaged tributaries. Evaluate data and reassess the monitoring programs every few years.

- Establish and periodically resurvey cross sections in large tributaries.

- Take aerial photographs every year to monitor changes in basins of ungaged tributaries.

Tributary Studies

The goal of tributary studies would be to develop a general method which can be used to accurately estimate the delivery of sand and coarse debris from gaged and ungaged tributaries through time. The objectives would be to:

- Determine long-term trends or cycles in tributary floodplain storage that would affect sediment delivery. Evaluate flow and sediment delivery history for variations or trends with time.

- Develop a general model for magnitude and frequency for debris, hyperconcentrated, and stream flow in tributaries.

Sand Deposit Studies

The goal of sand deposit studies would be to better define the response of sand-dependent responses to changing flow conditions. We suggest that investigations:

- Document flow and sediment changes with discharge at selected study sites. Measure flow velocities inside recirculation zones and in the main channel. Investigate changes in flow pattern and sand deposit response to changing flows. Investigate the use of water and sediment tracers to measure exchange between the main channel and recirculation zones.

- Consider the use of physical and mathematical models as a supplement to field measurements to investigate processes within recirculation zones and between the main channel and recirculation zones. Modeling should be done in close association with field studies to ensure that models reflect what is known or learned about the system and that insights gained from modeling are incorporated into the field studies.

- Consider the use of field studies under analogous conditions to investigate eddy processes. Field locations with similar processes but of smaller scale offer the possibility of collecting data under more favorable logistical conditions.

Main Channel Processes

The goal of main channel research would be to improve the accuracy of estimates of main channel sand storage and transport and to determine the significance of changes in river hydraulics at rapids to sand storage and transport.

- Use additional data collected in the monitoring program to evaluate results of sediment transport models and to refine models based on improved knowledge of sediment transport, tributary delivery, and storage of sand.

- Refine the conceptual model of main channel bed change based on improved knowledge of main channel transport and tributary delivery gained through the monitoring programs.

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BIOLOGY REPORT

Appendix B

CHUB
LCR
KOLB 1911

Emery Kolb holding three strings of chub (*Gila* sp.), Little Colorado River, Colorado River Mile 61.5, circa 1911. Photo courtesy of the Emery Kolb Collection, Northern Arizona University, Flagstaff, Arizona.

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SECTION I: INTRODUCTION AND MAJOR FINDINGS

The Biology Subteam Report describes the impact of past and present operational patterns of Glen Canyon Dam on the aquatic and terrestrial riparian communities of the Colorado River in Glen and Grand Canyons. It summarizes and integrates the results of 13 biological studies that were initiated as part of the Glen Canyon Environmental Studies (GCES) in 1983. The GCES was designed to be a preliminary investigation that would lead to long-term research and monitoring or a more formal assessment of the impacts of Glen Canyon Dam on downstream resources. Two primary questions were addressed by the biological studies:

(1) Do dam operations significantly affect the living systems downstream of Glen Canyon Dam?

(2) Does the potential exist to operate the dam in a manner that would enhance or protect biological resources?

The answer to both of these questions is yes for all of the biological resources studied, although the degree to which they are affected, and the degree to which modified dam operations will benefit them, differs from resource to resource.

The results of the individual biological reports have been integrated here in a way that describes how riverine communities respond to dam operations as well as how individual aquatic and terrestrial resources are affected by specific dam operations. Individual studies focused on components of the aquatic community, as well as the terrestrial riparian (streamside) communities that are dependent on water and nutrients supplied by streamflow. Desert habitats outside the river-influenced riparian zone were not within the scope of the studies. Similarly, tributaries were only studied near their confluence to the mainstem river.

This report begins with a historical perspective that gives a general overview of how the terrestrial and aquatic communities along the river changed after the construction of Glen Canyon Dam. Following the overview is a description of the design of the biological studies and the natural history of target resources. The major portion of the report is a discussion of how current dam operations affect individual resources. Next, a discussion of alternatives to current operations includes modified operation scenarios for each resource that minimize the deleterious effects of dam operations. In addition, non-operational alternatives that may mitigate the impacts of dam operations are presented, as well as data gaps and uncertainties in the analysis. Finally, a discussion of appropriate research and monitoring to refine management alternatives is presented.

SECTION II: HISTORICAL PERSPECTIVE

Changes Caused by Glen Canyon Dam

The construction of Glen Canyon Dam dramatically changed a number of the physical characteristics of the Colorado River, and in turn the aquatic and terrestrial riparian communities influenced by the river. Pre-dam river flows were characterized by seasonal changes in magnitude, turbidity, and temperature. Low flows occurred in the fall and winter and floods of turbid water occurred in spring and summer. The typical pattern was for peak flood flows to occur in late spring, with gradually declining flows, punctuated by thunderstorm runoff, through the summer. Water temperature ranged from near freezing in winter to 80 degrees F in the summer.

The pattern of post-dam flows is much different. Seasonal changes in flow magnitude, temperature, and turbidity are much less. However, dam operations now result in daily fluctuations in flow magnitude that were not present before dam construction. Spring floods, an important component of pre-dam flows, were absent for 20 years from the time of dam closure until Lake Powell filled in 1980, and have occurred since then only in reduced and modified form. In addition, most of the sediment carried by the river is now trapped in Lake Powell, drastically reducing the sediment and nutrient load of post-dam flows. Water temperature now ranges from 46 to 54 degrees F year-round with much less seasonal fluctuation than characterized pre-dam temperatures, but with a gradual increase in temperature with distance downstream from the dam.

Aquatic System

Dramatic changes in the character of post-dam releases led to a major shift in the aquatic food base. Pre-dam primary production of algae within the river was limited by turbid water, which minimized light penetration for most of the year. The pre-dam aquatic food base, therefore, depended largely on terrestrial input and was probably composed of detritus, terrestrial and aquatic insects, and other organic matter carried into the river. At present the dam is a barrier to sediment and other sources of organic matter from upstream tributary flow. The shift from turbid water to clear water has increased light penetration and increased the importance of algae, primarily

Cladophora, as primary producers at the base of the food chain. Living organisms associated with *Cladophora*, such as midges, *Gammarus*, and diatoms, are important food organisms for trout and other fishes (Carothers et al. 1981).

Decreased post-dam water temperatures caused a shift in the fish community from predominantly native warm-water species to a community dominated by cold-water fishes and fishes with wide temperature tolerances. Of the eight native species historically found in the Colorado River in Grand Canyon, several (Colorado squawfish, bonytail chub, roundtail chub, and possibly razorback sucker) have been extirpated (Carothers et al. 1981). The native species that have persisted in the changing river environment (humpback chub, speckled dace, flannelmouth sucker, and bluehead sucker) are generally restricted to warmer-water habitats such as tributaries and backwaters during certain portions of their life cycles. Humpback chub in particular now has a reduced distribution, and its reproduction appears to be restricted to one major tributary, the Little Colorado River (Kaeding and Zimmerman 1983).

Most of the exotic fish species in Grand Canyon were introduced before construction of Glen Canyon Dam (McDonald and Dotson 1960). The first known introduction of exotic fish into the Grand Canyon was the appearance of common carp prior to 1894. Trout were stocked in tributaries of the Colorado River from 1920-1971 by the National Park Service and other state and federal agencies. Other exotic species, which colonized from the tributaries or were transported in as bait fish by anglers, also became established in the pre-dam river. These included channel catfish, largemouth bass, bluegill, green sunfish, mosquito fish, plains killifish, and black bullhead. Warm summer water temperatures during the pre-dam era supported several of these exotic species throughout the river, but they declined after construction of the dam along with native, warm-water fishes. The post-dam decrease in water temperature, however, permitted an increase in the abundance and distribution of cold-water species such as rainbow and brown trout (Maddux et al. 1987).

Riparian Vegetation

The post-dam decrease in frequency and magnitude of floods has permitted vegetation to colonize nearshore areas (Turner and Karpiscak 1980). Before construction of Glen Canyon Dam, the terrestrial habitat along the Colorado River was characterized by three distinct vegetational zones running parallel to the river (Figure B-1A). Closest to the river was an annually scoured riparian zone supporting only ephemerals and short-lived woody plants; farthest from the river was the true desert vegetation, uninfluenced by the highest river flows. Between these two zones was the Old High Water Zone (OHWZ) vegetation, a stable pre-dam riparian plant community. The lower boundary of the OHWZ was maintained by scouring floods which removed seedlings and saplings, and the upper limit was most likely determined by soil moisture levels and soil depth. Currently above River Mile 40, the OHWZ is dominated by Apache plume, netleaf hackberry, and redbud. Below River Mile 40 this community is dominated by western honey mesquite and catclaw acacia.

OLD WATER PLANT COMMUNITIES MILE 40 IS THE BREAK

Tamarisk, an exotic tree, was found scattered just below the OHWZ vegetation at the upper limit of the scour zone. Tamarisk was introduced into the western United States in the late 1800s, and was common (but not dominant) along the Colorado River in Grand Canyon by approximately the 1920s (Clover and Jotter 1944).

The post-dam decrease in peak flows allowed the development of an extensive new plant community in the former scour zone (Figure B-1B). Referred to as the New High Water Zone (NHWZ) community, this new riparian vegetation is dominated by tamarisk as well as several native species, including coyote willow, arrowweed, and seep-willow. Though the OHWZ remained unaffected by the initial change in flow regime, mesquite and acacia seedlings are now establishing in the NHWZ more extensively than in the OHWZ.

The post-dam decrease in flooding also allowed the establishment of cattail and reed marshes in low-lying areas of the NHWZ. Marshes were rare or absent along the river prior to the dam, as indicated by 1965 aerial photographs and historical accounts. However, marshes may have been transient features of the riparian plant community that sporadically developed in the pre-dam scour zone during the years between large scouring floods. Over 40 acres of marsh habitat were present along the river by 1975 (Brown and Schmidt In preparation).

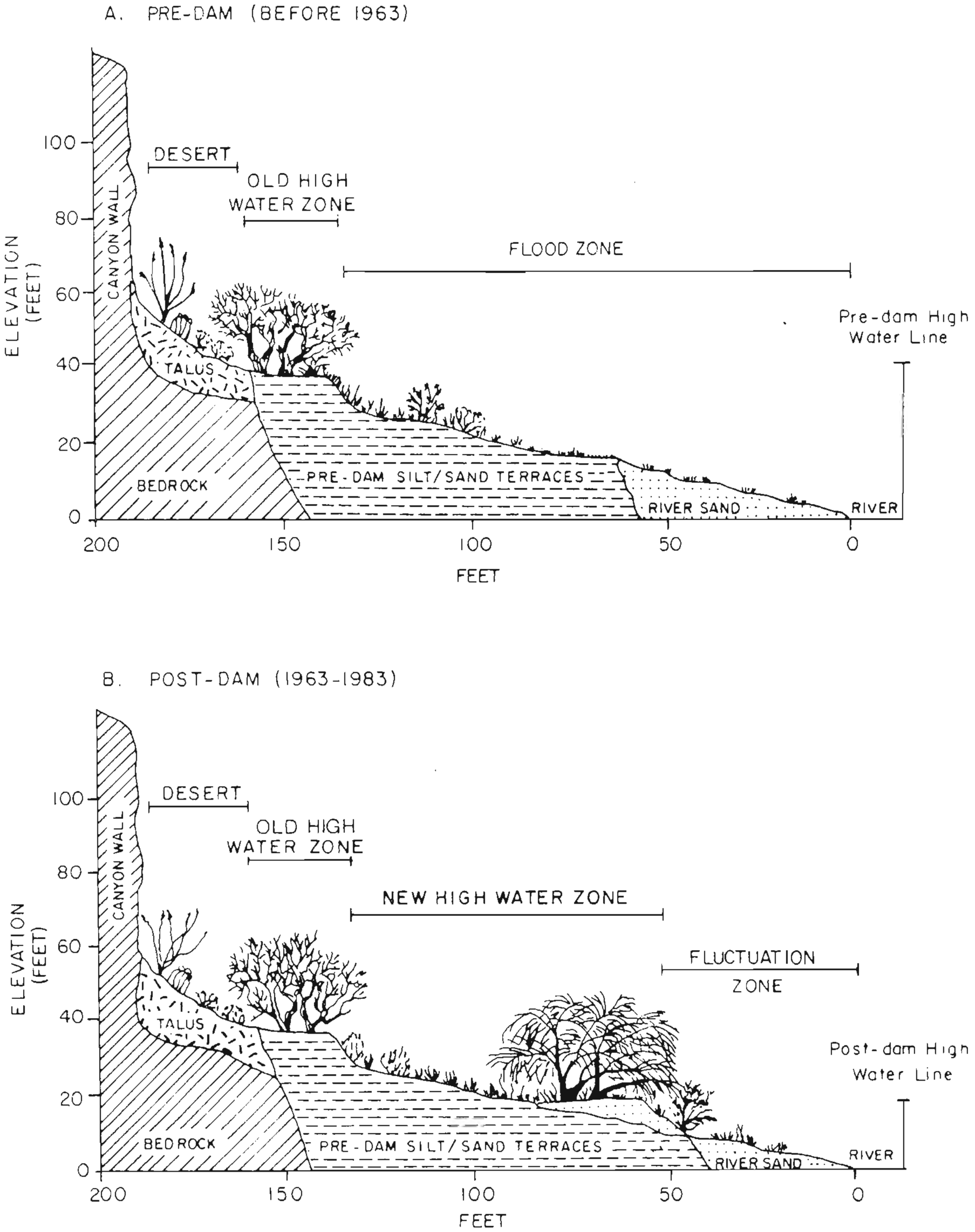

Figure B-1. The New High Water Zone vegetation colonized post-dam sand deposits above the zone of fluctuating flows.

Riparian Birds

The developing NHWZ more than doubled the extent of riparian vegetation available as bird breeding habitat along the river. Breeding birds quickly colonized the NHWZ, increasing in both number and diversity. The increase in diversity was due mainly to the development of new habitats, such as marshes, tall riparian trees, and dense shoreline vegetation, that were formerly rare to absent along the river. Bell's vireo, hooded oriole, great-tailed grackle, and summer tanager expanded their ranges hundreds of miles upriver to take advantage of the new vegetation (Brown et al. 1987). Other species, including common yellowthroat, yellow warbler, and yellow-breasted chat, which had always been present along tributaries moved into the river corridor. By 1982, the populations of at least ten species of breeding birds along the river were estimated to be five to ten times greater than before construction of the dam (Brown et al. 1987).

Other Riparian Vertebrates

The pre-dam vertebrate community was apparently characterized by species which were associated with low-elevation riparian areas dominated by mesquite. However, little or no quantitative data from the pre-dam river corridor exists for riparian vertebrates.

SECTION III: DESIGN OF THE GCES BIOLOGICAL STUDIES

Previous biological studies related to the operation of Glen Canyon Dam were initiated in the 1970s by the National Park Service (NPS), Bureau of Reclamation (BOR), the Arizona Department of Game and Fish (AGF), and the U.S. Fish and Wildlife Service (FWS). NPS studies concentrated on vegetation, fish, and wildlife (Carothers and Atchison 1976), while BOR/AGF studies focused mainly on trout. The early AGF studies dealt with the 15-mile trout fishery below Glen Canyon Dam and examined potential problems associated with fluctuating flows (Persons et al. 1985). Additional studies of available trout habitat at different flows were conducted by the BOR during peaking power investigations in the early 1980s (Wegner 1987). FWS studies focused on the life history of the humpback chub in the Little Colorado River (Kaeding and Zimmerman 1983).

Following the decision to uprate the Glen Canyon Dam generators, an interagency biological team was formed to develop research plans, determine costs, and initiate the biological studies program. The BOR, NPS, AGF, and FWS were the primary members of the team. Although study objectives were formulated by the interagency group, study methodology and design were developed by individual researchers--except for the fisheries research, which was designed jointly by the BOR, NPS, and AGF. Where practical, the new studies incorporated methods that were compatible with previous studies to provide continuity for data comparison and monitoring. Two other interagency study teams were formed to study sediment and hydrology and recreation. Interaction among the three teams was continuous throughout the entire biological program to ensure that data needs and logistic requirements were identified and correlated effectively.

Aquatic Studies

Aquatic studies were coordinated by the AGF and centered on ecology of fishes and the fish food base (Maddux et al. 1987). Over 30,000 fish were measured, weighed, and marked by tags or fin clipping. These data were used to evaluate the importance of main channel and tributary reproduction, patterns of habitat use, and seasonal patterns of reproduction. Research focused on the two fish species of major concern to the participating agencies: the endangered humpback chub and the economically important rainbow trout.

Several additional studies were contracted to individuals to answer questions that arose from the initial AGF research. Habitat availability for native fish was determined by aerial still and video photography which censused the number of different nearshore fish habitats available at low (5,000 cfs) and high (28,000 cfs) flows (Anderson et al. 1987). Habitat availability for trout was modeled for different dam releases by instream flow analysis of the reach between Glen Canyon Dam and Lees Ferry (Wegner 1987). The analysis determined the high and low flow extremes which could result in loss of habitat for trout fry and adults. Temperature simulations of a multi-level dam intake structure were conducted to determine the seasonal range of temperatures possible from such a structure at releases of 28,000 cfs (Ferrari 1987).

Trout food resources were looked at in several studies. Usher et al. (1987) examined the distribution of the algae Cladophora, a key primary producer, and determined its desiccation! tolerance for different periods of exposure to air. Zooplankton distribution in the river was surveyed to determine whether zooplankton was produced in the river or transported into the canyon from Lake Powell (Haury 1987; Maddux et al. 1987). The effects of steady versus fluctuating flows on dislodgment and movement of aquatic macroinvertebrates were also studied (Leibfried and Blinn 1987; Usher et al. 1987).

Terrestrial Studies

Substantial changes in riparian vegetation occurred as a result of the 1983 flood, which reached 97,200 cfs at Lees Ferry. Several studies were designed to examine the effects of this flood and evaluate the response of riparian vegetation to scouring and inundation resulting from high water.

Five vegetation studies examined vegetation dynamics at different scales, different study sites, and in different communities. Two of these studies used aerial photography to measure vegetation trends. Long-term changes in riparian vegetation cover were determined by measuring vegetated area over 19.2 river miles on large-scale aerial photographs from 1965, 1973, 1980, and 1985 (Pucherelli 1987). Very large scale aerial photography (1:250) was used to measure vegetation recovery from the 1983 flood on eight individual camping beaches covering 3.4 acres (Brian 1987).

Several ecological studies focused on the responses of individual species to changing flows. Plant mortality, soil nutrient loss, and insect population changes resulting from the 1983 flood were studied in 47 previously marked NHWZ study sites covering nine acres (Stevens and Waring 1987). Establishment, survivorship, and growth of seedlings and saplings, as well as growth, survivorship, and reproductive patterns of adult riparian plants, were followed for three years after the 1983 flood in these sites (Waring and Stevens 1987), and with over 200 belt transects and over 900 marked individuals in the NHWZ and OHWZ (Anderson and Ruffner 1987).

Studies of terrestrial vertebrates emphasized selected indicator species of birds and reptiles that were potentially sensitive to river flow regimes. The decision to focus this effort on birds and reptiles was based on several factors: (1) the time needed for long-term vertebrate population studies was greater than the time alloted for the studies; (2) comprehensive mammal studies were considered too costly compared to avian research; and (3) many vertebrates are dependent on the availability of riparian habitat and food resources, and they are likely to respond to changes in riparian habitats in a similar manner. Riparian birds were selected as indicator species to integrate the cumulative effects of flows and vegetation changes on vertebrates. Quantitative information on! the presence and numbers of riparian birds was available from previous research (Carothers and Aitchison 1976) and could be readily incorporated into a new study related to impacts of dam operation. Avian research focused on the abundance, diversity, and habitat use of riparian nesting birds (Brown 1987; Brown and Johnson 1987). Over 500 bird nests were located and measured to determine the distribution and habitat preferences of different species.

Reptile studies focused on the species composition, distribution, and habitat use of lizards in the riparian system (Warren and Schwalbe 1987). Reptiles were studied because little pre- or post-dam information was available on this group. Lizards were selected as indicator species because they were abundant in a variety of riparian habitats, and they used the shoreline zone. Lizard populations were sampled at 25 locations during three years with over 300 belt transects.

Though no comprehensive studies of terrestrial invertebrates were undertaken, the effect of the 1983 flood on some insect groups, primarily plant-feeding insects, was examined (Stevens and Waring 1987). Since insects are important food resources for vertebrates, the lack of information on terrestrial and aquatic insect ecology is a serious gap in our understanding of the terrestrial food base.

SECTION IV: NATURAL HISTORY OF BIOLOGICAL RESOURCES

The aquatic and riparian communities of the river corridor have had over 20 years to adjust to the changed river environment brought about by the completion and operation of Glen Canyon Dam. These are no longer completely native communities adapted to pre-dam conditions. Both the aquatic and terrestrial riparian communities now include naturally reproducing exotic species that have increased in abundance since the construction of Glen Canyon Dam.

This section of the report provides basic information on the critical elements of the life cyles and ecology of selected resources of the aquatic and riparian communities. Information necessary for understanding the effects of river flow regimes is presented for each resource separately.

Aquatic Community

Algae and Invertebrates

Food resources of Colorado River fishes in Glen and Grand Canyons vary among species, life stages, habitats, and seasons of the year. Early life stages of mainstream fishes largely feed on **zooplankton** (microscopic open-water organisms). The major source of zooplankton appears to be Lake Powell, although backwaters of the Colorado River may also be important sites of zooplankton reproduction (Maddux et al. 1987). Very little is known of the food resources of early life stages of fishes in tributaries to the mainstream river.

As Colorado River fishes increase in size, they are capable of eating larger food items, and bottom-dwelling organisms become more important in their diet. The filamentous green **benthic** (bottom dwelling) alga, Cladophora glomerata is of major importance to many species, including rainbow trout and, apparently, humpback chub. Cladophora is thought to be of little nutritive value to some fishes, in particular trout, but it serves as a substrate for attached **diatoms** (microscopic algae) that may have greater food value. It is also a habitat for important benthic invertebrate food items, such as the amphipod Gammarus lacustris and immature chironomid midges. Diatoms in turn form an important dietary component of these invertebrates (Maddux et al. 1987).

Large-scale fluctuations in discharge not only expose river bottom to the atmosphere, but also affect the velocity of river currents. Under extreme fluctuations, **drift** (dislodgment and movement) of *Gammarus* increases dramatically (Leibfried and Blinn 1987). This can have the short-term benefit of increasing availability of food resources to trout which feed on invertebrate drift. However, drift also increases mortality of algae and invertebrates. If the additional mortality exceeds the reproductive and recolonization capacity of these populations, negative long-term effects will occur to the food base. Mortality suffered though drift is not an absolute loss, however, because this organic matter can become part of the downstream foodbase.

Humpback Chub

The humpback chub (*Gila cypha*) is the only remaining endangered, federally protected fish species in Grand Canyon. This species remains endangered because only isolated and remnant populations exist throughout its range.

Grand Canyon humpback chub begin life in the Little Colorado River (LCR), but many occupy the mainstem Colorado River for much of their adult lives. Chub were observed spawning in May and June during this study, but other sources indicate that chub may spawn as early as March (Carothers et al. 1981). Following spawning, the eggs hatch within several days and the larval fishes grow approximately two inches by fall. At this size, the young fishes are capable of moving from the LCR into the colder mainstem river where they occupy backwater and nearshore, low-velocity habitats. Humpback chub obtain sexual maturity in 3-4 years at approximately 10 inches (Kaeding and Zimmerman 1983).

Most humpback chub living in the mainstem river return to the LCR to spawn (Kaeding and Zimmerman 1983). The mouth of the LCR at its confluence with the main river may be an important staging area for spawning adults (Maddux et al. 1987). Some spawning may occur in mainstream habitats, but cold water temperatures probably prevent successful hatching (Kaeding and Zimmerman 1983). In contrast, the seasonally warm temperatures in the LCR provide a suitable environment for successful hatching, larval survival, and growth (Maddux et al. 1987).

Adults are found in both the Little Colorado and mainstem Colorado. However, it is not known whether all young fish move into the mainstem river to live or whether some stay in the LCR as year-long residents. Tagging and recapture of a small number of adult chub confirmed that movement between the mainstem Colorado and the LCR does occur (Maddux et al. 1987). The actual extent and direction of such movement remains largely unknown.

Decreased water temperature since closure of Glen Canyon Dam has been a major factor restricting humpback chub spawning and larval rearing in the LCR, which has spring and summer water temperatures of between 61-75 degrees F. Because of the remoteness of the humpback chub populations, there has been little previous research on their breeding ecology and microhabitat requirements for spawning. Other tributaries in Grand Canyon warm to temperatures suitable for spawning, but are not known to support reproducing populations of humpback chub (Maddux et al. 1987). In the Upper Colorado River Basin, humpback chub spawning and larval rearing take place in mainstem river habitats and not in tributaries (Miller et al. 1981). This suggests that humpback chub may have used the mainstem Colorado River in Grand Canyon for spawning and larval rearing prior to the closure of Glen Canyon Dam.

Because their reproduction is restricted to the LCR, the humpback chub population is now extremely vulnerable to any changes in that watershed. Spawning and rearing of larval humpback chub occur from early spring through late summer. Therefore, many of the mature spawning adults as well as their offspring are congregated in the LCR during this period. If some natural or man-caused catastrophe were to occur to the LCR at this time, a major portion of the population could be lost. The reliance of the humpback chub on the LCR makes them more vulnerable to major perturbations than other native fishes, which use a wide variety of habitats for spawning and larval rearing.

Common Native Fishes

Of the eight native fish species formerly found in the Colorado River below Glen Canyon Dam, only three species remain common: speckled dace, bluehead sucker, and flannelmouth sucker. Two others, humpback chub and razorback sucker, are rare in occurence. Razorback sucker apparently does not reproduce in Grand Canyon and soon may be extirpated from this reach of the Colorado River. Three species are already extirpated from the Grand Canyon: Colorado squawfish, bonytail chub, and roundtail chub (Maddux et al. 1987).

The three common native fishes spawn throughout the mainstem river and its tributaries in late spring and early summer (Maddux et al. 1987). However, low mainstem river temperatures restrict the distribution of larval fishes to backwaters which have lower velocities and warmer temperatures. Sampling of backwater habitats in Grand Canyon has shown that they are used by juvenile humpback chub and other native fishes. Backwaters are shallow basins that are connected to the mainstem river, but have little or no current. In backwaters, water temperatures exceed those in the adjacent river, ranging up to greater than 70 degrees F in the summer.

Under steady flow conditions, backwaters may develop both plankton and insect communities which provide food for fishes. A backwater is usually formed by the return current channel of an eddy. As water level drops, the surrounding topography is exposed, and the channel becomes a backwater (see Appendix A, Figure A-2). Studies by the U.S. Geological Survey (USGS), which have been confirmed by aerial photography, suggest that antecedent flows prior to decreases in water levels may be a controlling factor in backwater formation. Under steady flows, sand in an eddy return channel is deposited with greater topographic relief, resulting in deeper, larger backwaters when flows drop. After the backwater is formed, its longevity is also influenced by river flow patterns. Backwaters disappear faster during periods of fluctuating water levels than under steady flows.

Rainbow Trout

The National Park Service (NPS) began introducing trout into the Grand Canyon in the 1920s. However, high pre-dam water temperatures in the mainstem Colorado River restricted trout populations to a few suitable tributaries. Post-dam river temperatures have decreased to 46-54 degrees F, allowing trout to colonize the mainstem river. The 15-mile river reach from the dam to Lees Ferry has became one of the finest trophy trout fisheries in the West. Downstream and tributary fisheries, which are also valued by anglers, are used less intensively and are less accessible than the Lees Ferry fishery. Maintenance of the Lees Ferry trout fishery under present management guidelines requires supplemental stocking, without which catch and harvest rates could not be maintained.

Rainbow trout spawning occurs primarily from November to February on mainstem gravel bars within 15 miles of Glen Canyon Dam and in several tributaries below Lees Ferry (Maddux et al. 1987). Once trout fry emerge from the spawning beds (redds), they move into low-velocity, nearshore habitats (Maddux et al. 1987).

With temperatures around 50 degrees F, the river below Glen Canyon Dam allows year-round growth and provides suitable temperatures for natural reproduction of rainbow trout. These temperatures, however, are lower than those reported for optimal trout growth. Optimal growth of rainbow trout, for example, occurs at 64.4 degrees F (Cherry et al. 1977). Temperatures up to 70 degrees F do not adversely affect trout feeding and other activities (Scott and Crossman 1973), although the potential for fish disease increases at higher temperatures (Piper et al. 1982).

Terrestrial Riparian Community

Vegetation

Most terrestrial animals along the Colorado River in Grand Canyon depend on riparian vegetation in some manner. Plants provide cover, foraging substrate, food, and nesting habitat for birds, insects, reptiles, and mammals.

The Old High Water Zone (OHWZ) riparian vegetation is dominated by acacia and mesquite. The extent of this community was limited to above the 100,000 cfs river level by scouring floods before closure of Glen Canyon Dam. Mesquite and acacia continue to be limited by flooding, but since post-dam floods are smaller and less frequent than pre-dam floods these plants have extended their distribution into the New High Water Zone (NHWZ). Mesquite and acacia are well established in the NHWZ, where individuals in younger age classes are most abundant (Anderson and Ruffner 1987).

The NHWZ is dominated by tamarisk, coyote willow, seep-willow, and arrowweed. It is more heavily used by animals than the OHWZ for several reasons. The NHWZ exhibits greater productivity, plant species diversity, and habitat diversity than does the OHWZ, and has a wider range of vegetation age classes. Higher productivity results from proximity to water, which supports greater biomass and faster-growing species. The OHWZ community is composed of small trees, shrubs, and herbs, whereas the NHWZ community contains small-leaved trees, broad-leaved trees, large and small shrubs, and subaquatic and terrestrial herbs.

The methods of plant reproduction also are more varied in the NHWZ. Many species can reproduce both vegetatively and by seed. Several species, including coyote willow, arrowweed, and spiny aster are clonal and reproduce primarily by vegetative means. The ability of these species to reproduce vegetatively and to grow quickly contributes to a potential for rapid colonization and change in species composition in the NHWZ (Stevens and Waring 1987). There is also greater variation in the timing of flowering, timing of fruiting, seed viability, and longevity in the NHWZ than in the OHWZ (Waring and Stevens 1987).

Woody plants in the NHWZ occur for the most part in small, single-species patches, which are clustered and create a mosaic of many different habitat types. Along a single river terrace, one might find a mixed tamarisk woodland, a dense cattail marsh, and patches of clonal species such as coyote willow and arrowweed. This greater habitat diversity potentially supports more animal species than the more uniform vegetation structure found in the OHWZ.

Post-dam changes in soil substrate could have long-lasting effects on riparian vegetation. Historically, flood flows carried high sediment loads that were deposited along the riverbank. Under post-dam flow, a much lower sediment load is carried by the river (Appendix A). As nutrient levels of riparian soils decrease due to leaching by sediment-free water, the species composition of riparian vegetation may change if some species become limited by low nutrient levels.

Insects

Three major insect communties are present in the riparian zone: aquatic insects, which depend on the water for part of their life cycle; fossorial, or ground-dwelling insects; and phytophagus, or plant-feeding insects. Insects are important in!the Grand Canyon ecosystem as food resources, decomposers, predators, and pollinators. For these reasons, changes in insect communities may have subtle but profound long-term effects on the entire riparian and aquatic ecosystems. Little is known about insect species composition, distribution, and population dynamics as related to dam releases.

Aquatic insects are important food resources for fish, birds, reptiles, and amphibians. Most of these insects have an aquatic larval stage followed by a terrestrial adult stage and are thus directly affected by river flows. Though little is known about aquatic insects in Grand Canyon, several critical aspects of insect population dynamics, such as total aquatic insect production, species composition, and the timing of insect emergence, could be dramatically affected by changing river flows. The movement of emergent aquatic insects into the riparian zone represents a major exchange of energy between the aquatic and terrestrial systems.

Many fossorial insects, especially termites, are plant decomposers and play a primary role in returning nutrients to the soil. They are also a food source for reptiles and amphibians. Ground-dwelling insects are susceptible to drowning during moderate to high floods but can reestablish their populations from surrounding unflooded areas. Little information exists on the species composition and ecology of these insects.

Plant-feeding phytophagus insects play several roles in the Grand Canyon ecosystem. In their larval stages they feed on plants and may limit plant productivity, especially in years of high insect abundance. Many adult phytophagus insects are plant pollinators and are necessary in plant reproduction. These insects are also an important food resource for vertebrates. Plant-feeding insects are limited by the health of riparian vegetation and are indirectly affected by dam releases. Changes in the moisture content of plants can lead to changes in species composition of associated insects, whereas inundation of plants increases insect mortality (Stevens and Waring 1987).

Lizards

Ten lizard species are found in the river corridor. Total lizard population densities are approximately ten times higher in shoreline habitats than in adjacent non-riparian habitats (Warren and Schwalbe 1987). Although most lizards are distributed in both riparian and non-riparian habitats, one species, the tree lizard, was observed only in riparian habitats.

Lizard reproduction is significantly higher in shoreline areas than in adjacent non-shore and non-riparian habitats. Maximum reproduction appears to take place in habitats such as cobble bars where fine beach sand is available for nest sites. Lowest reproduction occurs in densely vegetated and very rocky sites.

Reptile activity patterns are closely tied to ambient temperatures, with peak activity occurring along the river from April through September, and reproductive activity occurring primarily during June and July. These months of maximum activity in the shoreline zone are the time when lizards, and probably other reptiles, are most sensitive to fluctuations in river flow levels.

Riparian Birds

Of the nearly 30 species of birds known to nest in the river corridor, 11 species are referred to as **obligate riparian birds** due to their complete dependence on well-developed riparian vegetation in which to breed. Over 90 percent of the nests of obligate riparian birds were located in the NHWZ. Of the 11 obligate riparian species, 8 nested exclusively or primarily in the NHWZ (including American coot, willow flycatcher, common yellowthroat, yellow warbler, yellow-breasted chat, great-tailed grackle, and hooded and northern orioles). Only three species of obligate riparian birds nested in the OHWZ, Bell's vireo, blue grosbeak, and indigo bunting, but these three nested widely in the NHWZ as well. The NHWZ not only supported a higher density of birds, but supported the great majority of obligate riparian birds (Brown and Johnson 1987).

The remaining species of riparian birds which were not completely dependent on riparian habitat generally nested in both the NHWZ and OHWZ. Mourning dove, house finch, blue-gray gnatcatcher, Lucy's warbler, and Bewick's wren were among the more common species found throughout both communities. However, black-chinned hummingbirds nested almost exclusively in the NHWZ in the Grand Canyon, while phainopeplas nested exclusively in the OHWZ.

Bell's vireo, common yellowthroat, and yellow-breasted chat are the species most affected by river flows because they nest low to the ground and close to the water. Common yellowthroat nests are found 3 feet or less above the ground or water surface in low-lying marshy areas, while Bell's vireo and yellow-breasted chat nest in thickets of dense, young tamarisk shrubs and place their nests from 3-5 feet above ground. With the exception of American coot and mallard, other birds breeding in the river corridor nest higher in the vegetation, so that direct nest losses from inundation are uncommon.

Birds will quickly renest once, or even twice, if their initial nest is destroyed. Failure of a season's breeding attempts results in the loss of a generation of young birds and a reduced breeding population the following year. Vireos, yellowthroats, and chats are resilient, and will quickly recover in numbers through reproduction or immigration from surrounding areas as long as their preferred habitat remains intact.

Willow flycatcher is a species of special concern in the river corridor due to its rare status. Willow flycatchers have been greatly reduced in numbers in the Southwest as riparian habitat has disappeared. Fewer than 50 breeding pairs of willow flycatchers are known to remain in Arizona, the largest population of these occurring along the Colorado River in Grand Canyon (Unitt In press). Willow flycatchers nest close to the water in low-lying habitats dominated by tamarisk or willow, and may be very sensitive to the effects of changing flows.

Peregrine falcon, a Federally endangered species, nests in small numbers on cliffs along the river. Ducks, doves, and small songbirds are their principal prey, and increasing numbers of these breeding birds in the new tamarisk habitat could positively influence the well-being of falcons by increasing their food base.

SECTION V: IMPACTS OF CURRENT DAM OPERATIONS ON BIOLOGICAL RESOURCES

Floods and Fluctuations

The two aspects of current operations that have strongest effects on biological resources are flood releases and fluctuating releases. Floods are defined as releases greater than powerplant capacity. They are generally between 40,000 and 50,000 cfs and occur for four to six weeks in May and June (Figure B-2). They occur in years when runoff is well above average or the forecasted runoff is too low. Since the filling of Lake Powell in 1980, flood releases greater than 40,000 cfs have occurred in five of seven years. Under current operations, floods of this magnitude are expected to occur in one out of four years.

Fluctuations were a common aspect of operations during the filling period for Lake Powell, but they have been relatively uncommon during the course of the GCES. For the purposes of this report, fluctuations are defined as a change in dam release greater than 10,000 cfs in one day (Figure B-3). Both the rate at which water level changes during fluctuating flows and the magnitude of the peaks and troughs of fluctuations affect natural resources. The negative effects of fluctuations increase as the amplitude and rate of change increase.

Low, steady flows (less than 10,000 cfs) are also an aspect of operations that can affect biological resources. They have been uncommon during the course of the study and therefore are not evaluated for all resources. Where the effects of low flows could be determined for individual resources, the specific threshold levels and their effects on the resource are described below.

Fluctuations and floods directly affect the aquatic system (Table B-1). Fluctuations do not directly affect the terrestrial riparian system because vegetation is established above the level of the high water line. Floods, however, have a strong negative effect on vegetation and wildlife because river flow moves outside the established river channel, scouring vegetation and drowning wildlife (Table B-2).

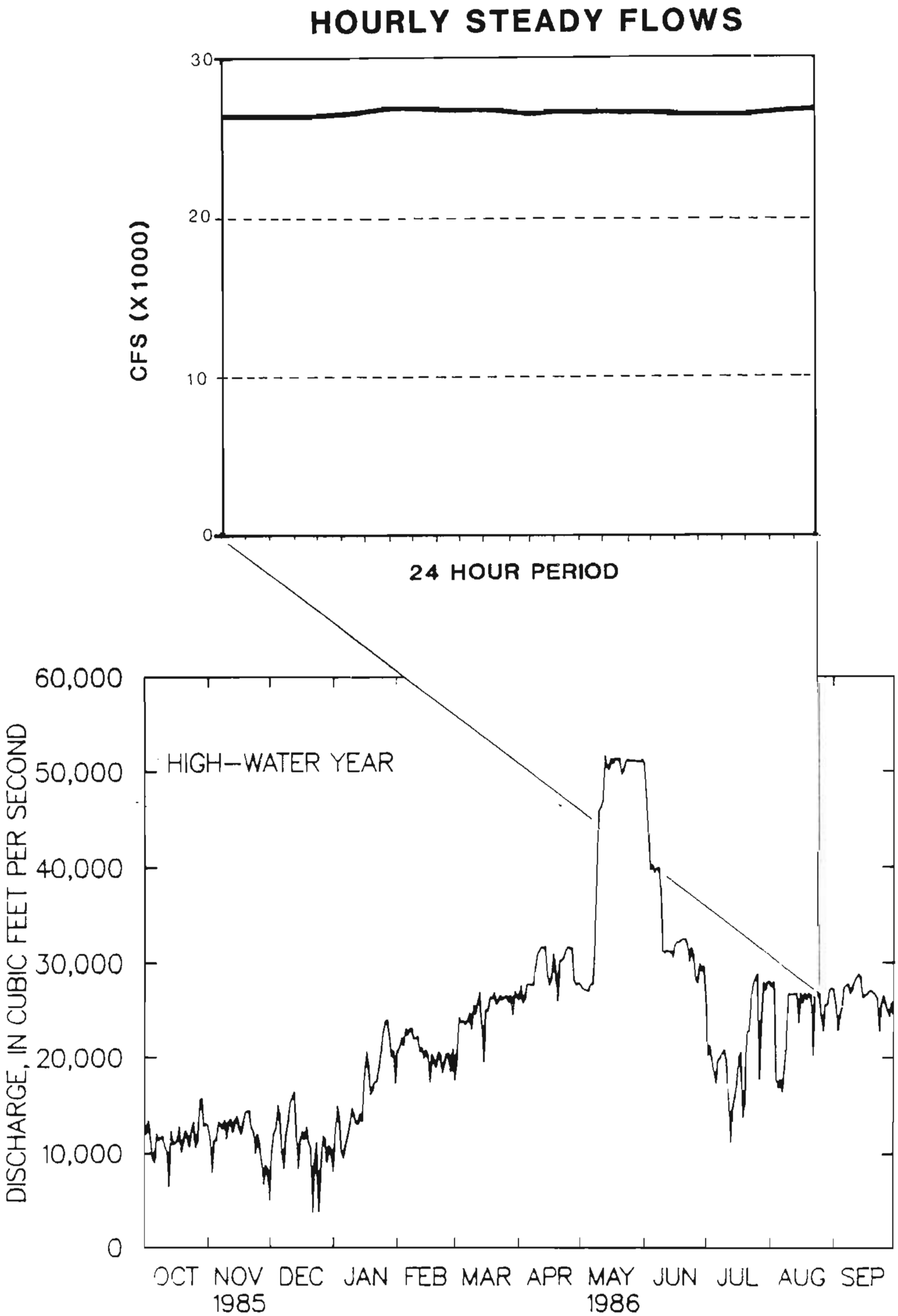

Figure B-2. Releases for 1986 represent current operations in a high-water year and illustrate flood flows and steady flows.

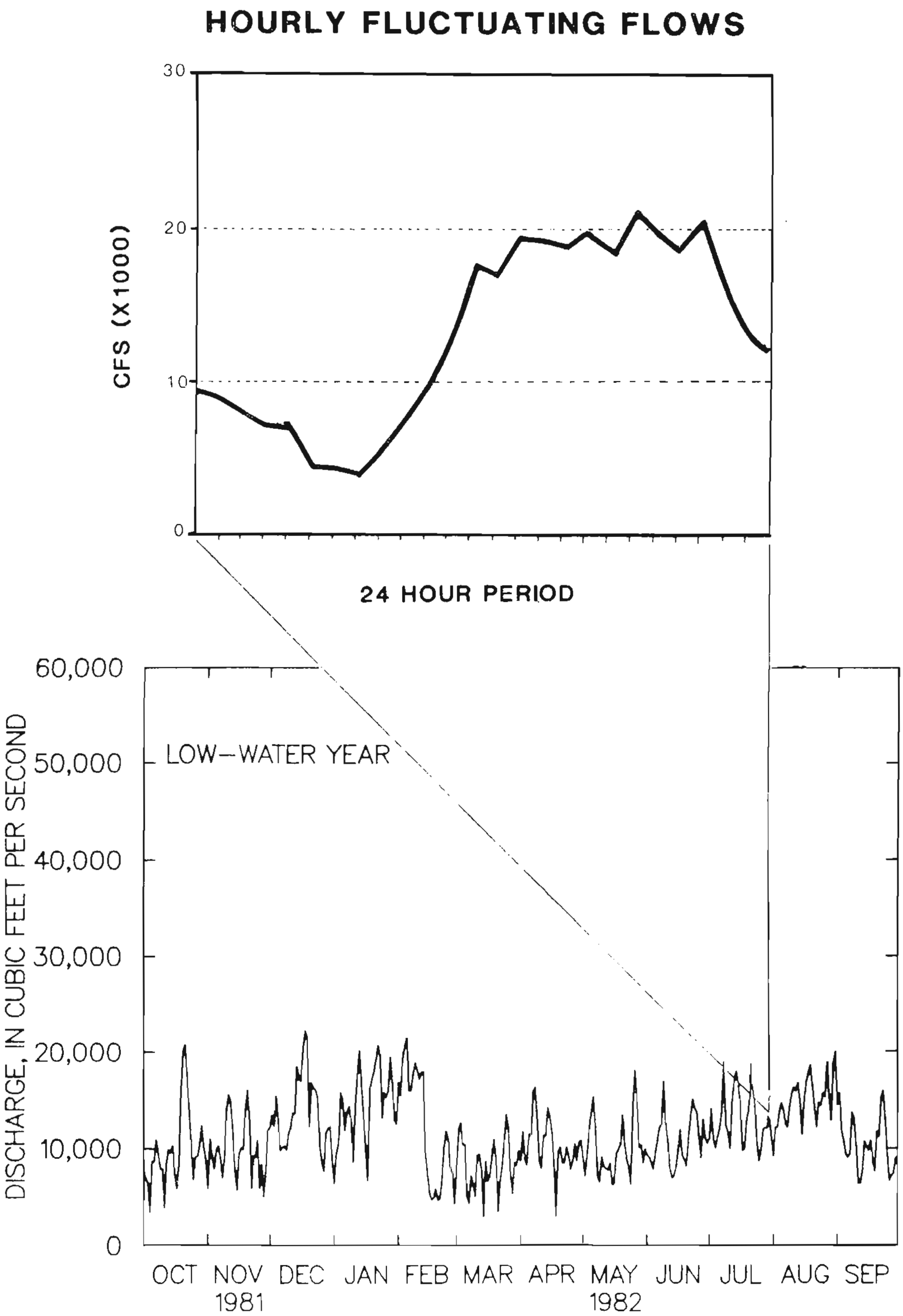

Figure B-3. Releases for 1982 represent current operations in a low-water year and illustrate fluctuating flows.

Table B-1. Impacts of dam operations on aquatic resources.

	Aquatic Foodbase	Humpback Chub	Common Native Fish	Rainbow Trout
Fluctuations	Desiccation of algae; increased drift of <u>Gammarus</u>, but decreased numbers in zone of fluctuation	Some stranding of juveniles, and erosion of back-waters used by juveniles.	Loss of spawning and rearing areas in main channel backwaters.	Stranding of all age classes; drying of spawning bars; increased food availability
Floods < 40,000 cfs	No known effect	Increased area for larval rearing at the mouth of the Little Colorado River; decreased number of back-waters for juveniles	No known effect; if floods occur in summer, rearing habitat in back-waters will be decreased	Loss of low-velocity habitat for juveniles prior to May 1
Floods > 40,000 cfs	Decrease in foodbase if algae is scoured	same as above	No known effect unless floods occur in summer	Loss of low-velocity habitat for juveniles prior to May 1

Table B-2. Impacts of dam operations on terrestrial resources.

	Vegetation	Riparian Birds	Reptiles
Fluctuations	Minimal decrease in areal extent of vegetation due to increased peak flow	No direct effects	No direct effects
Floods < 40,000 cfs	Increased mortality from inundation, scouring, and burial	Nests lost if floods occur between May and June	Minimal effects
Floods > 40,000 cfs	Decrease in individuals and plant cover; loss of marshes; decreased nutrient levels in soil	Substantial nest loss for many species; loss of nesting habitat, especially marshes; effects on insects unknown	Rapid increases in water level lead to drowning and nest inundation

Algae

When flows fluctuated or dropped for prolonged periods, Cladophora, the most abundant green algae in the river, and associated macroinvertebrates such as Gammarus were subject to detachment and desiccation. In order to determine the effects of prolonged exposure on Cladophora, samples were desiccated for 12 hours in laboratory experiments. Up to 57 percent of the biomass was lost (Usher et al. 1987). In a related experiment, invertebrate (including Gammarus) densities were found to decrease in areas along the river exposed during periods of fluctuating flows. However, Gammarus densities were unaffected in those areas that remained inundated during periods of fluctuation (Leibfried and Blinn 1987). Other important food organisms that were collected on drift nets, such as midges, were less affected by fluctuating flows.

Humpback Chub

Young size/age classes were present in the size distribution of humpback chub collected during 1985 and 1986, indicating that successful reproduction occurred during 1984 and 1985. Spring floods greater than 40,000 cfs during these two years approximated the pattern of pre-dam spring floods and may in part be responsible for successful reproduction and recruitment. High flows in the mainstem river during spring back up into the mouth of the Little Colorado River, creating a large area of ponded water and increasing the area of habitat available for rearing larval humpback chub (Maddux et al. 1987). In contrast, fluctuating flows during the spring could increase drift and movement of young chub into the mainstream. However, fluctuating flows did not occur during this time and their effects on humpback chub could not be adequately determined.

Juvenile chub used backwaters during spring, summer, and fall when backwater temperatures exceeded those of the mainstem river. Flows were steady throughout most of the study period and the effects of fluctuations on backwater use could only be measured for a few days in the fall. During this time, juvenile chub moved in and out of backwaters with fluctuations in flow and little stranding was observed (Maddux et al. 1987). However, fluctuations may disrupt reproduction of zooplankton in backwaters, thereby potentially limiting food availability for chub. In addition, fluctuations can erode backwaters and decrease warm-water habitat available for juvenile chub. There is no information on the long-term effects of daily displacement from warm backwaters to the cold mainstem on juvenile chub growth and survivorship.

Lowered water temperature due to the presence of Glen Canyon Dam may be the overriding factor limiting the size and distribution of the humpback chub population. In three years of sampling no larval humpback chub were found in the mainstem river, indicating that mainstem river temperatures are too cold to support successful reproduction and rearing (Maddux et al. 1987). It appears that larval chub either rear in the Little Colorado River or die upon moving into the mainstem.

Common Native Fishes

Larval native fishes are relatively immobile, very susceptible to predation, and require quiet, warm backwaters for growth and survival. As flows fluctuate, the depth, temperature, and velocity of backwaters change, forcing fish to either move into the mainstem river or be stranded and die (Maddux et al. 1987). Fluctuating flows increase the risk of predation and require additional energy expenditure by larval fishes. Fluctuating flows may also limit the development of new backwaters and accelerate the erosion of existing backwaters.

A census of backwaters using aerial photography showed a threefold increase in backwaters from 191 at high flows of 28,000 cfs to 575 at low flows of 5,000 cfs (Anderson et al. 1987). Both water levels censused were preceded by two months of steady flows. Steady flows redistribute sand to form well-defined eddy return channels that become backwaters when flows decrease. Sand deposited under fluctuating flows has less topographic relief, and therefore fewer backwaters are formed when flows are decreased (Appendix A).

Native fishes, primarily bluehead sucker, were found to use shallow gravel bars for spawning similar to those used by rainbow trout. Fluctuating flows during spawning could dewater these areas, leaving eggs exposed to air and predators and resulting in large egg losses. Fluctuations strand both larvae and adults in isolated backwaters and pools when releases drop quickly, leading to increased mortality.

Rainbow Trout

The major flow-related impacts to rainbow trout were mortality of eggs and larvae on the spawning bars, displacement of newly emergent fry, and stranding of all age classes. Flows of at least 8,000 cfs were required during trout spawning to keep the gravel bars inundated and to prevent desiccation of eggs and emergent fry (Persons et al. 1985). Even short periods of dewatering can result in 99 percent mortality of these early life stages (Maddux et al. 1987). Gravel bars were exposed on a daily basis during periods of fluctuating flows, which made them unavailable for spawning or resulted in delayed spawning. Natural reproduction contributed 28 percent of the trout harvest, accounting for an average of 12,000 trout harvested in 1984 and 1985 in Glen Canyon (Maddux et al. 1987).

Low-velocity, nearshore habitats are required by trout fry for rearing. These habitats changed in extent and structure under the influence of fluctuating flows, resulting in fry being exposed to velocities beyond their swimming abilities. As flow discharge increased, the area and number of low-velocity habitats decreased, potentially forcing trout fry to move long distances to other suitable habitats. This would require additional energy expenditure and increase the chance of mortality. As flows in the Lees Ferry reach rose above 12,000 cfs, the areas of low-velocity, nearshore habitats suitable for trout fry began to decrease, and virtually all fry habitat was lost when flows exceeded 25,000 cfs (Wegner 1987).

Rapidly decreasing discharges during peaking operations often left trout stranded on shore. Following a decrease in flow from near 23,000 cfs to 5,600 cfs in ten hours, more than 800 trout ranging in size from 4 to 22 inches were found dead in the Lees Ferry area as a result of stranding. Although adults were vulnerable to stranding during the spawning periods, the smaller trout were generally more susceptible to stranding because of their preference for shallow, nearshore habitats (Maddux et al. 1987).

Fluctuations increased the short-term amount of food available to trout by increasing drift of invertebrates. The number of <u>Gammarus</u> in drift nets increased four-fold from 10.7/hr to 42.3/hr during a 17-hour rise in flow from 5,300 to 25,000 cfs (Leibfried and Blinn 1987). During another period of fluctuating flow in October 1984, the number of Gammarus in trout stomachs increased seven-fold (Maddux et al. 1987). A similar increase in the proportion of invertebrates in trout stomachs occurred during a period of fluctuating flow from December 1985 to February 1986 (Maddux et al. 1987). However, due the short period of fluctuations it was not possible to determine whether the increase in drift was a response to seasonal changes or fluctuations or whether the higher levels of drift would be maintained under a long-term fluctuating flow regime.

Vegetation

Vegetation near the water's edge in the NHWZ was most affected by floods. The 1983 flood, which reached 97,200 cfs, reduced overall vegetation cover by 30-50 percent (Brian 1987; Pucherelli 1987). Vegetation maps created from aerial photography for a total of 19.2 river miles showed a decrease in vegetated area from 112 acres in 1980 to 77 acres in 1985 (Pucherelli 1987). A similar analysis of eight camping beaches showed a decrease in vegetated area from 2.7 acres to 1.3 acres between 1982 and 1984 (Brian 1987). In addition, 50 percent of over 14,000 individual plants monitored on 47 quadrats covering nine acres were killed (Stevens and Waring 1987). Major factors in plant mortality were direct removal of plants through scouring, drowning, and burial by deposition of sand as flows receded. Marshes, which were particularly sensitive to flooding, were reduced by 95 percent during the 1983 flood (Brown and Schmidt In Preparation).

NHWZ vegetation showed high rates of germination after flooding, with extensive recolonization at 21 out of 49 sites (Waring and Stevens 1987). Highest rates of germination occurred at the water's edge, leaving the new seedlings susceptible to continued flooding (Anderson and Ruffner 1987). Marshes have shown no substantial signs of recovery due to extensive scouring of the eddies where they occurred (Brown and Schmidt In Preparation).

The OHWZ is established higher on the banks, above the pre-dam flood level, and therefore was less affected by post-dam flooding. Vegetation maps from aerial photography showed a statistically significant decrease of 17.6 percent in OHWZ vegetation over 19.2 river miles from 1980-1985 (Pucherelli 1987) and an insignificant increase in OHWZ vegetation of 8.4 percent on eight camping beaches from 1982-1984 (Brian 1987). Flood flows did bring water closer to this pre-dam community, yet growth rates and reproductive output of adult mesquite and acacia did not increase after the 1983 flood. No increase in seedling establishment occurred in the OHWZ following the 1983 flood (Anderson and Ruffner 1987).

An important potential effect of floods on vegetation is the loss of soil nutrients. Measurements of NHWZ alluvial terraces before and after the 1983 flood showed a three-fold decrease in soil organic matter from 1 percent to 0.4 percent (Stevens and Waring 1987). Soil texture also changed as a result of flooding. The proportion of small sized soil particles (silts and clays) important in holding water in the soil decreased from 22 percent to 10 percent (Steven and Waring 1987). Post-flood changes in soil particle size distributions were correlated with a decrease in seedling growth rates (Waring and Stevens 1987, Figure B-4). With repeated flooding, nutrients will be leached from the soil to the point where their absence may affect long-term productivity and species composition of vegetation.

Spring flooding changed the species composition and decreased diversity of NHWZ vegetation through differential mortality of some species (Steven and Waring 1987) and by favoring recruitment of tamarisk over native NHWZ species which germinate later in the summer (Waring and Stevens 1987).

Insects

Floods and fluctuations appeared to reduce the abundance of chiromomid midges, an important food resource for birds, reptiles, and other insects (Stevens and Waring 1987). Since many midges live in _Cladophora_ beds, the factors that reduce biomass of _Cladophora_, such as scouring from floods and desiccation from fluctuations, could also decrease midge abundance.

Riparian Birds

The 1983 flood inundated most common yellowthroat nests and severely scoured marshes, their preferred nesting habitat. Marshes have shown little recovery since that time. For this reason, yellowthroats are not expected to recover to pre-flood numbers until marshes recover.

Bell's vireo also lost some nests to inundation at flows of less than 40,000 cfs. However, most breeding birds nested higher and were not affected until flows exceeded 40,000 cfs. At flows of 90,000 cfs, 75 percent of the 300 Bell's vireo nests and 50 percent of over 100 yellow-breasted chat nests were lost to inundation.

The greatest long-term impact to birds is the potential loss of nesting habitat through streambank erosion, especially the loss of tamarisk in the NHWZ. The 1983 flood removed up to 50 percent of NHWZ vegetation. The impacts of repeated floods from 1983 to 1985 reduced Bell's vireo densities by 45 percent, due both to habitat loss through streambank erosion and direct losses from nest inundation. No bird species have been lost from the system due to habitat loss. Many obligate riparian species also nest along tributaries and could recolonize the river corridor provided that suitable habitat remains or is allowed to recover.

The extent, structural diversity, and species composition of vegetation are important to wildlife. While vegetated area may increase population sizes of wildlife, vegetation diversity is most likely to increase the diversity of wildlife. Structural diversity of vegetation may be tied to very infrequent floods that open patches of the NHWZ to recolonization by different species or younger individuals of the same species. The frequency of flooding that would increase structural diversity of vegetation is unknown. However, flooding has been shown to decrease vegetation diversity in the short-term. We know from this study that diversity within the bird community along the river was increasing from 1963 to 1982, a twenty-year period of operations with almost no flood releases. We do not know how long plant and animal diversity would have continued to increase or whether the flood in 1983 will increase or decrease diversity in the long-term. Therefore we can make no predictions of potential benefits of flooding without further study.

Lizards

Floods and fluctuating flows had short-term negative effects on shoreline lizard populations by trapping and drowning some individuals on alluvial bars and displacing others into habitats higher in the riparian zone when the water rose rapidly (Warren and Schwalbe 1987). Daily fluctuations will increase lizard mortality, especially when flows rise at night when lizards are inactive. Shoreline nest sites may also be inundated by floods and fluctuating flows during the breeding season from May to July. In spite of the potential loss of large numbers of individuals during flood events, lizard populations in shoreline habitats had densities ten times higher than adjacent non-riparian habitats within 10 months after the 1983 flood. Immigration from adjacent riparian habitats probably contributed to rapid population recovery in the shoreline zone.

Seasonal Sensitivity of Resources

Flows that may be detrimental to a certain biological resource at a specific time of the year may have minimal effects at other times (Table B-3). Breeding seasons were the most sensitive period of the life cycle for birds and fish. Once young birds had successfully left the nest and were able to take care of themselves, flood flows no longer directly affected them in the short-term. Over the long-term, however, floods that reduce the extent of vegetation or habitat diversity can affect the numbers and kinds of birds.

Egg and fry stages in the life cycle of fish were susceptible to mortality when stranded because of fluctuating flows. The mortality associated with stranding would be minimal if those same fluctuations occurred when spawning had been completed and the young were mobile enough to escape.

In contrast, vegetation and reptiles can be negatively affected by any flood regardless of season. However, if small floods coincided with high tributary flow in summer they could replenish soil nutrients by depositing silts and clays on existing sandbars and benefit vegetation in the long-term.

Resource Resilience

The long-term resilience of a population, or its ability to recover from disturbance, can be just as important as how sensitive individuals are to that disturbance in the short-term. For example, common yellowthroats may lose a year's reproduction due to spring floods, but the population can recover quickly because population sizes are large and new individuals can immigrate from adjacent areas. In contrast, the humpback chub may not be able to recover easily from large reductions in its spawning population because the dam has isolated the Grand Canyon population from other populations that could contribute individuals through immigration.

The resilience of the vegetation community is of basic importance to the overall resilience of terrestrial vertebrates because vegetation loss greatly affects those animals which use the vegetation as habitat. For example, bird and reptile populations are very resilient to disturbance in one year as long as their preferred habitats remain or recover and are available the following year.

Although marshes were scattered throughout the canyon, marsh communities have not yet recovered from the effects of the 1983 flood. The relatively low resilience of marsh habitats may be due to subsequent flooding in 1984, 1985, and 1986, or to a loss of substrate in areas where marshes formerly occurred (Brown and Schmidt In preparation).

Table 6-3. Summary of the flow sensitive aspects and effects of flows on natural resources.

Resource	Flow Sensitive Aspect	Sensitive Period	Deleterious Operations
Humpback Chub	Habitat area for reproduction and larval rearing at the mouth of the Little Colorado River	May - June	Low Flows
Common Native Fish	Number and stability of backwaters for larval rearing	June - August	Fluctuations High Flows
Rainbow Trout	Spawning and stranding of all age classes in the mainstem and tributaries	December - February	Fluctuations
	Availability of low-velocity habitats for fry	January - April	High Flows
Vegetation	The areal extent of NHWZ vegetation and nutrient levels of soil	All Year	Floods Peak Flow
Riparian Breeding Birds	Nesting and rearing; availability of nesting habitat; Food resources during the breeding season	April - July	Floods
Reptiles	Potential for drowning	All Year	Floods

SECTION VI:
IMPACTS OF THE UPRATE AND REWIND PROGRAM

The Uprate and Rewind Program at Glen Canyon Dam increased the peak generating capacity from 31,500 cfs to 33,100 cfs. Impacts to the biological resources resulting from the use of this increase is contingent upon specific changes in duration of flows, their stage, and the amplitude and rate of change in fluctuations. It is not possible at this time to specify precisely how the new powerplant capacity will affect future dam operations. Variability in the forecast, management options, and equipment limitations will affect the actual release schedule. Accurate evaluation of the Uprate and Rewind Program cannot be made pending a refinement of actual dam operations.

Vegetation that still persists in the canyon down to the 27,500 cfs flow elevation will eventually be lost under current operations (L. Stevens pers. comm.). Vegetation established at this lower level over the years because the 31,500 cfs (capacity) flow was released only on rare occasions. By averaging stage/discharge relationships at four USGS gaging stations in Grand Canyon, the zone of vegetation loss which would result from an increase in peak flow from 27,500 cfs to 33,100 cfs was estimated as one to two vertical feet (Appendix A). No species of terrestrial vegetation or wildlife are likely to be lost by this increase in stage; however, a decrease in areal extent of vegetation would occur. The number of nesting birds and other wildlife may decrease as vegetational area decreases.

Vegetation that would be affected by the increase to 33,100 cfs resulting from the Uprate and Rewind Program was severely affected by flood flows of 1983 to 1986. Large areas of NHWZ vegetation were lost as a result, and this in turn led to a decrease in the number of nesting birds. The impact of a decrease in areal extent of vegetation due to increasing peak capacity to 33,100 is likely to be minimal relative to the damaging effects of floods.

Several aspects of increasing peak operating capacity could affect the aquatic community. An increased amplitude of fluctuations possible under a 33,100 cfs maximum or an increase in the rate of change in water level during fluctuations could increase the number of stranded fish and increase the erosion of backwaters. If increased peak capacity also increases the probability of flows below 14,000 cfs, this could increase reproductive losses for rainbow trout by exposing and drying eggs on spawning bars during low flows. Any increase in peak capacity should be monitored to directly determine impacts on! biological resources.

SECTION VII: MODIFIED OPERATIONS

A series of scenarios was developed to minimize future impacts or to enhance the long-term viability of the terrestrial and aquatic biological resources downstream of Glen Canyon Dam. These scenarios focus on the seasonal flow requirements of humpback chub, common native fish, trout, and terrestrial vegetation and wildlife (Figures B-4 to B-7). The flow requirements of the scenarios are based on findings of the GCES and were developed around the sensitive life stages and seasonal habitat requirements of each species or group of species (Table B-3). For example, a sensitive life stage for humpback chub is the May to June spawning period. High flows are beneficial to humpback chub spawning, indicating that maximum powerplant releases be maintained through May and June. Flow requirements for the remainder of the year are baseloaded to evenly distribute the total annual release during high- and low-water years. Flows are steady rather than fluctuating because stable flows have less impact on the overall biological system. The scenario for combined biological resources (Figure B-8) evaluates the trade-offs of providing preferred flows for certain species while balancing the impacts to other species. This scenario does not appear in the final report because it represents only one of many ways in which flow requirements of different resources could be combined.

Future research and monitoring may necessitate changing the maximums or minimums of the scenarios as well as seasonal flow or fluctuation requirements because high, steady flow conditions during the study period resulted in some uncertainties and limitations in the data. For example, flood flows (>31,500 cfs) occurred concurrently with good humpback chub spawning success in the Little Colorado River. Yet, the maximum flow recommended for humpback chub during May and June is limited to the 31,500 cfs powerplant capacity (Figure B-4). This ceiling was put on the operating scenario recommended for humpback chub spawning because (1) pooling at the mouth of the Little Colorado River would still occur, if to a lesser extent, with the 31,500 cfs limit; (2) flood flows during May and June would substantially reduce the amount of water available for release during the remaining months of the year; and (3) almost all other biological resources would be adversely affected by such flood releases each spring. Because of the level of uncertainty associated with the real need for a spring flood release, future research on humpback chub would need to focus on verification of the recommended flow requirements of the mainstem river.

Humpback Chub

Fishery data collected during May and June show that high, steady flows create and maintain a large ponded area of still water at the mouth of the Little Colorado River. This ponded area increases the availability of low-velocity, warm-water habitat for sexual maturation and larval rearing. Humpback chub reproduction, growth, and larval survival may be enhanced in such an environment.

Due to a lack of information on the effects of fluctuating flows, no additional flow requirements have been identified which would benefit humpback chub during the remainder of the year. Figure B-4 shows the scenario for humpback chub for a normal (8.23 maf) and high (16.6 maf) runoff year. The period July through April in the scenario exhibits steady flows to distribute the available water. Although some juvenile humpback chub could be lost to stranding during fluctuations from July through April, other effects of fluctuations are not well understood.

Common Native Fish

June, July, and August are the best months to provide low-flow rearing habitat for larval bluehead sucker, flannelmouth sucker, and speckled dace (Figure B-5). This 5,000 cfs, non-fluctuating, 90-day period would benefit these fishes by at least tripling the available backwater habitat when compared to higher flows. The steady flows would also allow native fishes to remain in these warmer, protected backwater environments rather than repeatedly exposing them to the colder mainstem river as protected habitats expand and recede during fluctuations. The availability of these low-velocity, warm-water habitats to larval native fishes would decrease energy expenditure, increase food, and reduce vulnerablity to large predators.

Larval native fishes reach sufficient size by the end of August to allow them to survive in the mainstem river. After this time, native fishes are less susceptible to impacts from changes in river stage and fluctuation.

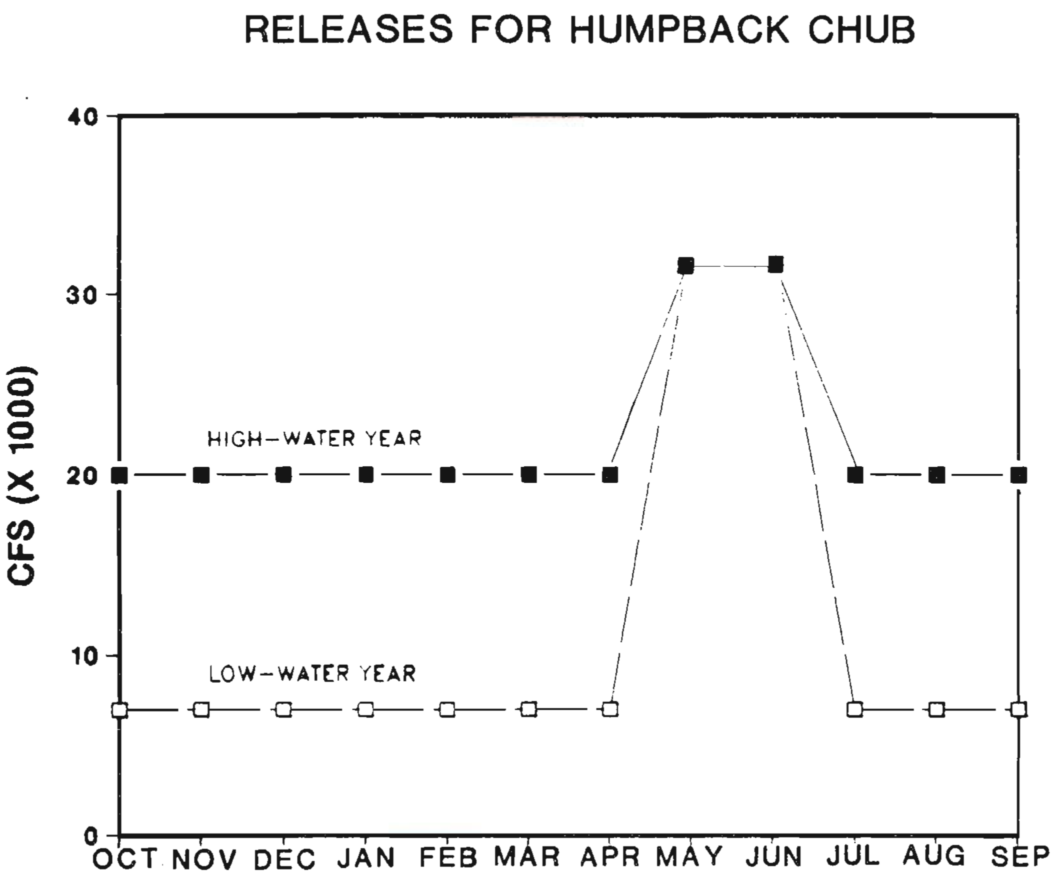

Figure B-4. Releases for **HUMPBACK CHUB** call for high flows in the spring.

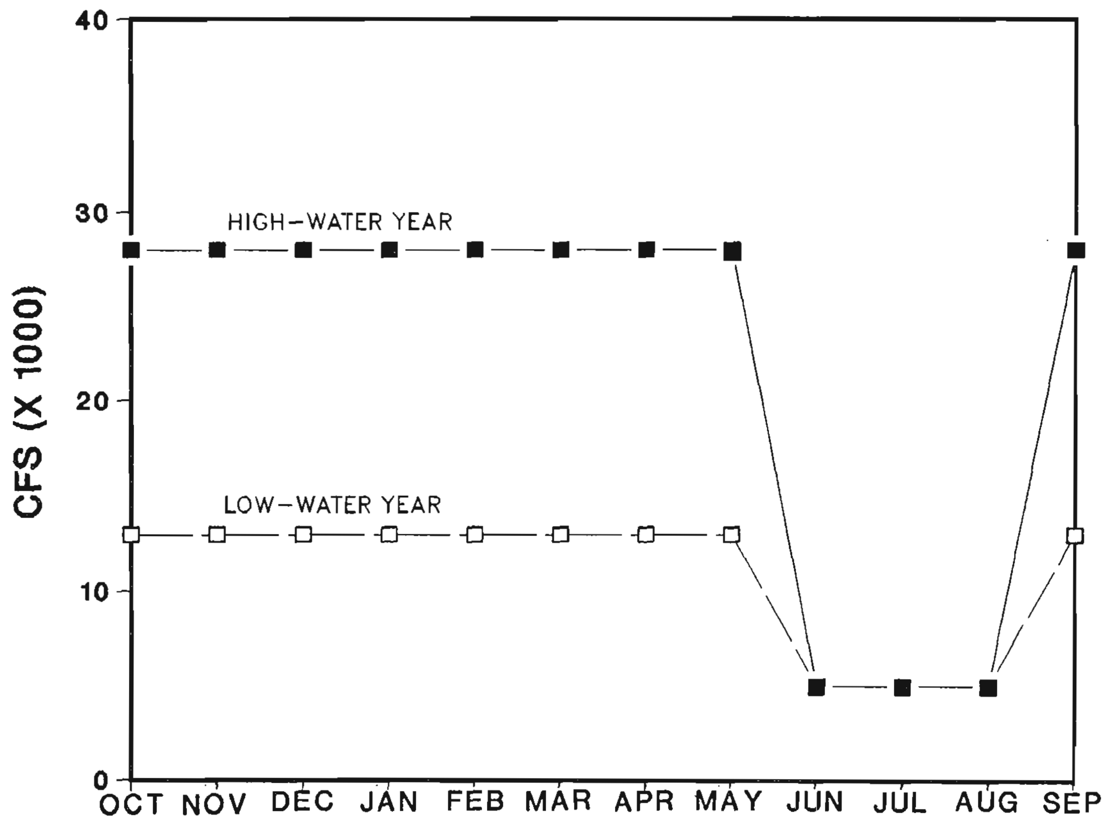

Figure B-5. Releases for **COMMON NATIVE FISH** call for low flows in summer.

Rainbow Trout

Balancing the seasonal needs of trout may require both fluctuating and steady flows at specific times of the year (Figure B-6). Fluctuating flows may be beneficial to trout growth because fluctuations increase drift of macroinvertebrates, thereby increasing food availability. A higher proportion of macroinvertebrates were found in trout stomachs during fluctuating flows than during steady flows. The frequency and timing of fluctuations that would maximize trout growth are not known, and as a result the scenario presented here calls for fluctuations when they would have minimal negative impact to other biological resources.

Fluctuating flows are deleterious in winter and spring while trout are spawning. Steady flows during this period are necessary to prevent increased mortality of eggs and fry through periodic dewatering of the gravel bars where spawning occurs. Conservative rates of fluctuation are preferred to rapid fluctuations, which strand adults and all other age classes throughout the year.

An 8,000 cfs minimum flow is required to inundate the gravel beds used for spawning. As minimum flows fall below 8,000 cfs in the winter and spring, spawning beds are exposed and natural reproduction decreases. The incremental loss in natural reproduction as flows fall below 8,000 cfs is not known.

Once fry have emerged from spawning areas in March, a minimum flow of 8,000 cfs is no longer necessary. In order to protect trout fry, however, maximum flows should not exceed 25,000 cfs from January to April, since high flows decrease the availability of nearshore, low-velocity rearing habitats.

Natural reproduction contributes approximately 28 percent of the trout harvest in the Glen Canyon fishery. The cost of replacing these fish through stocking has not been determined.

Terrestrial Vegetation and Wildlife

The scenario for vegetation and wildlife would eliminate floods, which are detrimental to terrestrial resources, and fluctuations, which indirectly impact terrestrial resources (Figure B-7). The elimination of fluctuations would reduce peak flows and increase the areal extent of NHWZ vegetation by allowing

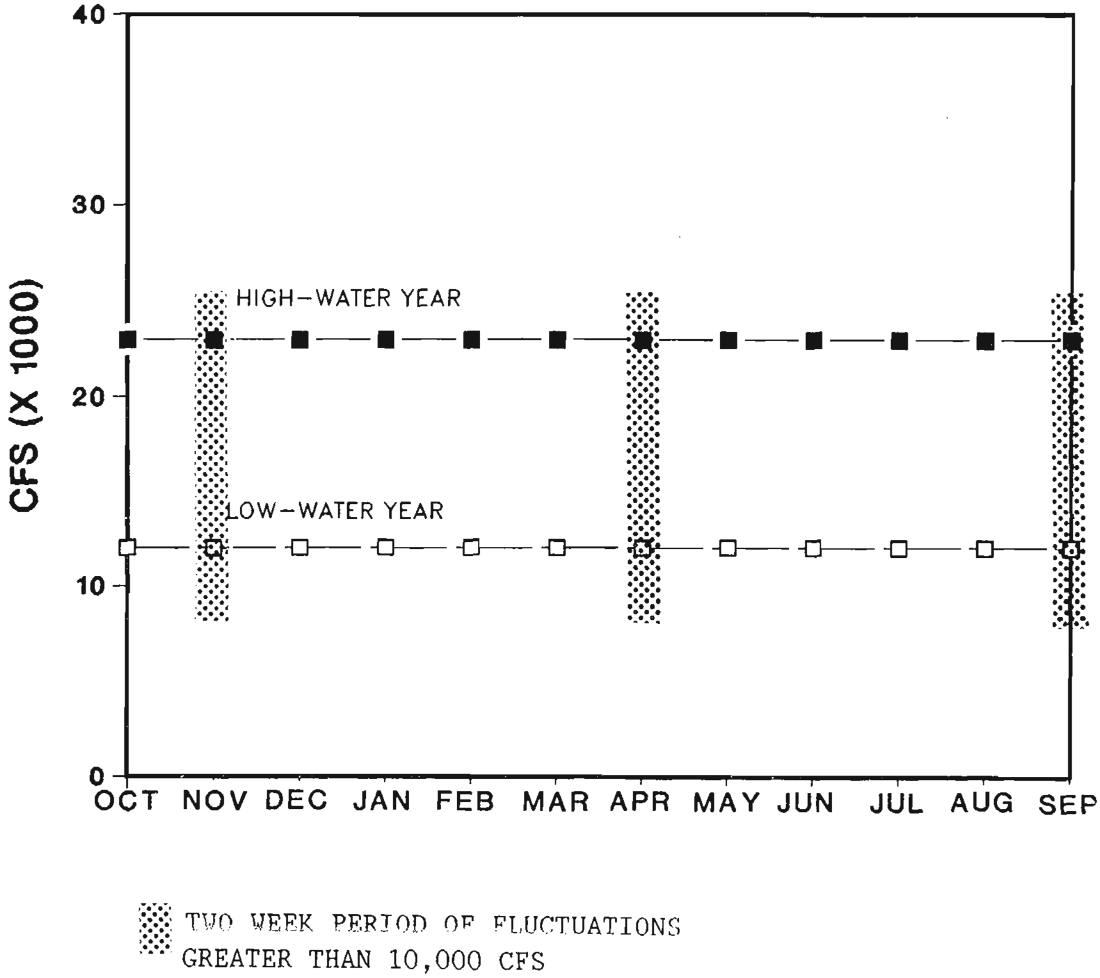

Figure B-6. Releases for **RAINBOW TROUT** call for baseloaded flows with short periods of fluctuation.

colonization down to the 23,000 cfs level. Increased vegetated habitat could also increase population sizes of terrestrial animals. This is evidenced by the fact that the number and diversity of nesting riparian birds increased greatly as the extent of NHWZ vegetation increased after the construction of Glen Canyon Dam.

Insects are an important food source for wildlife and have substantial effects on plants through predation and pollination. The effects of this scenario on insects are unknown.

Combined Biological Resources

Aquatic resources are directly affected by all flows, and because of their greater sensitivity they are favored in the scenario for combined biological resources (Figure B-8). This scenario also protects terrestrial resources because it would eliminate floods, the major negative influence on the terrestrial ecosystem. A scenario which combined flow requirements for all biological resources could include high flows for humpback chub, low flows for larval native fishes, fluctuating flows for trout growth, minimum flows to protect trout spawning, and elimination of flooding to reduce vegetation scouring and bird nest loss. Allowing fluctuations and steady flows to 31,500 cfs for trout and humpback chub, however, would limit the colonization of terrestrial vegetation to above this level. An additional trade-off would require the reduction of the low-flow period for native fish rearing from three to two months to enhance reproduction of humpback chub by providing high flows in June. Since bluehead and flannelmouth suckers are more widespread and spawn in a greater variety of habitats than humpback chub, protection of the endangered chub population could be considered to be more important.

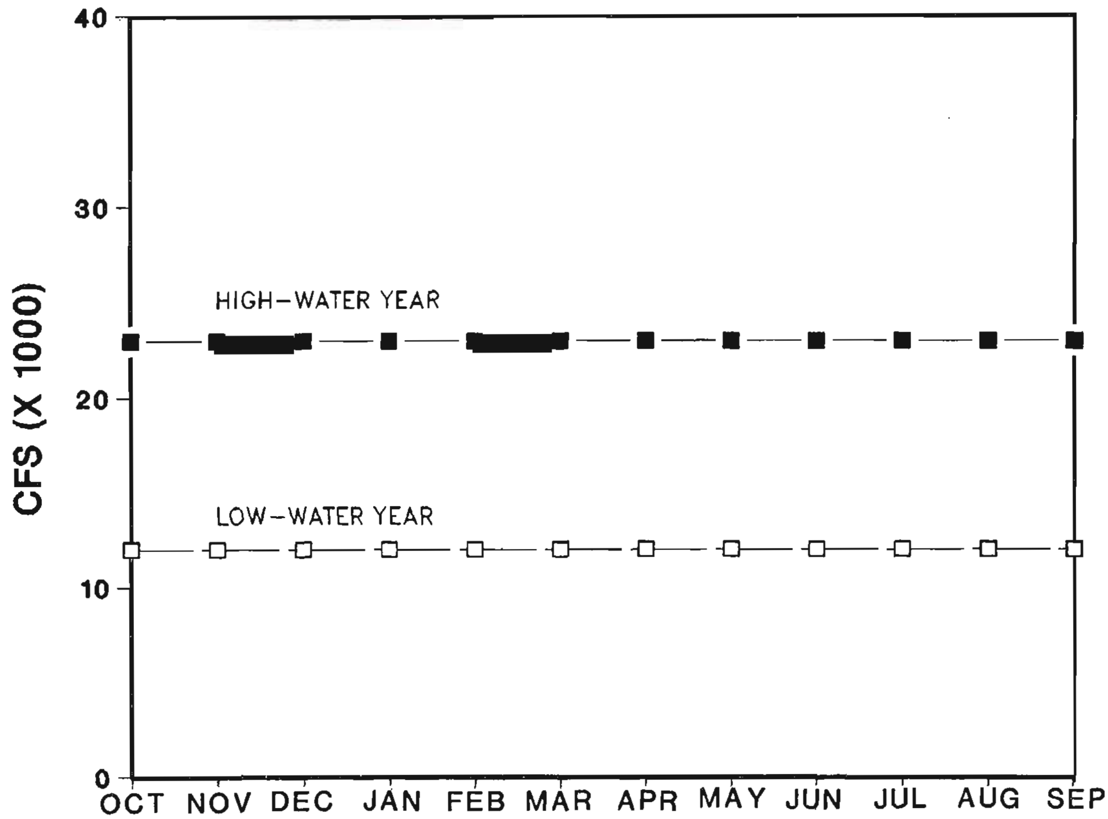

Figure B-7. Releases for **TERRESTRIAL VEGETATION AND WILDLIFE** call for baseloaded flows.

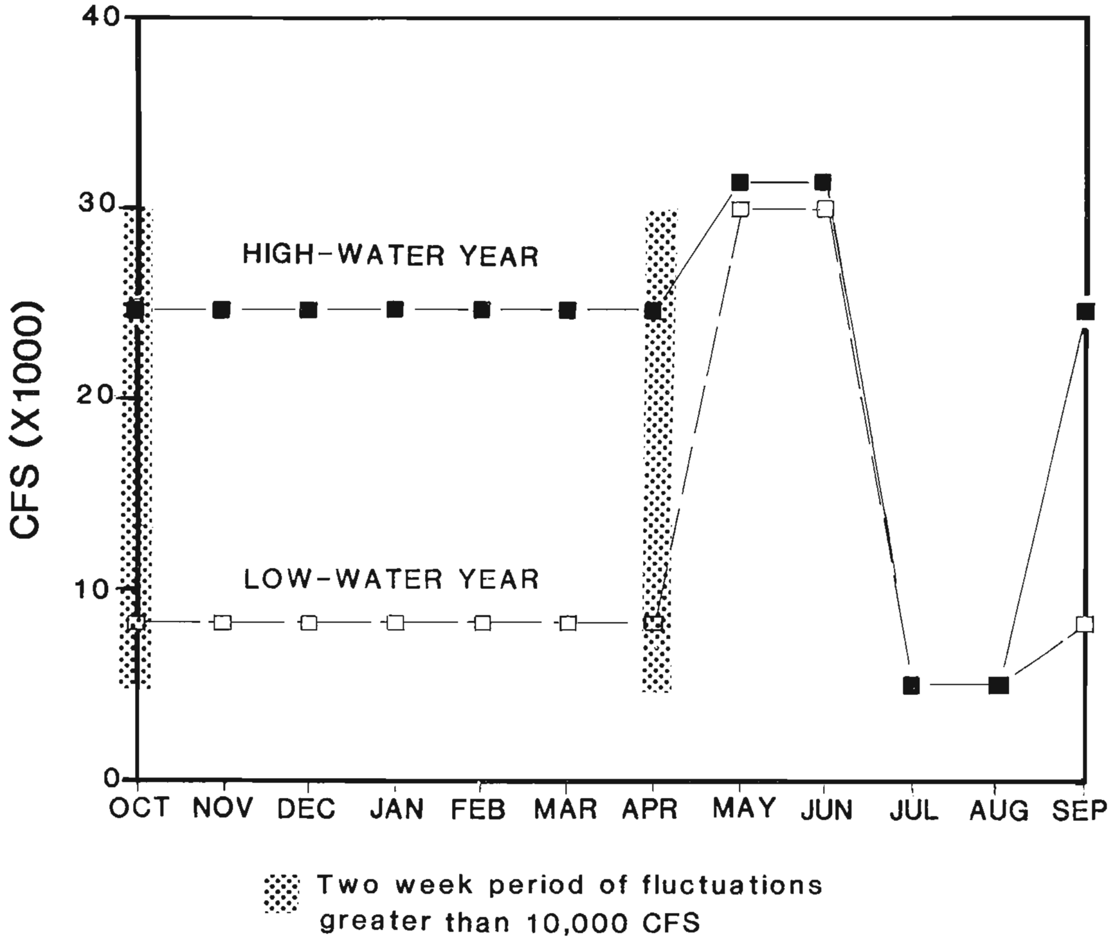

Figure B-8. An example of a release pattern for **COMBINED BIOLOGICAL RESOURCES** favors aquatic resources.

SECTION VIII: NON-OPERATIONAL ALTERNATIVES TO PROTECT OR ENHANCE BIOLOGICAL RESOURCES

There are several non-operational alternatives which could be implemented to offset operational impacts to biological resources.

Supplemental Stocking of Trout

The requirement for providing a minimum release of 8,000 cfs to improve natural reproduction of trout can be relaxed by providing additional hatchery fish through supplemental stocking. Supplemental stocking in the Lees Ferry reach could reduce conflicts between providing fluctuating flows for trout growth and maintenance of steady flows to protect natural reproduction. However, stocking probably would not replace losses to the downstream trout fishery in the Grand Canyon. In addition, other strains of rainbow trout which spawn during spring or summer when flows are generally higher could be evaluated.

Increased Water Temperature

If water temperature in the mainstem were increased to 62 degrees F during May and June, the humpback chub population might be able to expand its spawning and rearing area to include the mainstem Colorado River. This would reduce dependence on the relatively small area of spawning habitat in the Little Colorado River. In addition, increased water temperature could allow reintroduction of endangered fish species such as the Colorado squawfish that were lost to the river after construction of Glen Canyon Dam.

Pre-dam summer water temperatures ranged from approximately 65 degrees F in May to a peak of approximately 80 degrees F in July and August, and dropped to approximately 70 degrees F in September. Preliminary results from temperature modification models indicate that the maximum temperatures attainable while releasing 28,000 cfs through a multi-level intake structure range from 55 degrees F in May to approximately 70 degrees F in September, 10 to 20 degrees below pre-dam temperatures. Humpback chub spawning is currently initiated at temperatures above 61 degrees F in the Little Colorado River. The optimum temperature range for spawning, 61 to 68 degrees F, can be reached with the multi-level intake structure, but would be delayed at least one month over pre-dam seasonal patterns because of the time required to increase reservoir temperatures. Some portion of the humpback chub population could adjust to a later spawning, since the natural spawning seasons of many fish species are flexible and often vary with yearly temperature differences.

Increasing water temperature would increase seasonal growth rates for native fishes and trout. In addition, increased water temperature would increase the availability of warm-water habitats with low velocity required for rearing of larval native fish. This increase in habitat could reduce native fish dependence on backwaters, thereby reducing the need for low flows during rearing.

Any attempt to increase temperature to benefit native fishes could also lead to population increases of competing, warm-water exotic fish species such as shiners and sunfishes which could directly compete with native fishes for space and food. This may have long-term negative impacts on native fish populations. The reservoirs immediately above and below the study area contain species of concern, including striped bass, walleye, channel catfish, and smallmouth bass. If successful, these fishes could become predators on humpback chub and other native fishes. Introduced fishes have successfully competed with and preyed upon native fishes in other portions of the Colorado River Basin (Kaeding 1986; Wydowski 1987).

Optimal temperature ranges for native fishes are higher than those for trout. Though an increase in water temperature would seasonally increase trout growth rates, temperatures above approximately 75 degrees F are lethal to trout (Cherry et al. 1977). A significant change in water temperature could also affect species composition and productivity of the trout food base.

Structural Reestablishment of Marshes

The high floods in 1983 eliminated 95 percent of the marshes along the river. These specialized habitats which were rare or absent before the construction of Glen Canyon Dam are important in maintaining high vertebrate diversity. If they do not recover naturally, structural measures could be used to artificially recreate the marshes that were present between 1963 and 1983 if they do not recover naturally. Since little is known about marsh formation or ecology in Grand Canyon, research would need to be conducted prior to considering any structural features.

SECTION IX: DATA GAPS AND UNCERTAINTIES IN PREDICTIONS

Prediction of the impacts of dam operations on natural resources and recommended actions to reduce these impacts are based on data collected during the course of the GCES studies as well as on the findings of previous studies. Where data were insufficient or study design failed to provide necessary information, biologists formulated assumptions based on general ecological understanding. Through the combined use of observation, related research and literature, and extrapolation, researchers have tried to minimize uncertainties and fill gaps in understanding. Nonetheless, several factors limit the accuracy of this analysis and are described below.

Studies Conducted During a Period of Transition

The initiation of the biological studies took place at a time when the dam operations were in a period of transition between the reservoir filling phase and the current operational phase. Prior to the filling of Lake Powell in 1980, operations placed a high priority on releasing as little water as possible in order to allow the reservoir to fill. The result was a strongly controlled release schedule with fluctuating flows in a predictable annual cycle. A full reservoir and unusally wet weather from 1983 to 1986 caused a series of high-flow years in which excess water had to be released from the dam, causing downstream floods and high, steady flows.

Analysis of impacts resulting from flow fluctuations was severely limited by the small period of time when dam operations fluctuated more than 10,000 cfs in 24 hours. For the period of 1963-1983, fluctuations occurred 77 percent of the time; however, during the study period, fluctuating flows were available only 31 percent of the time. When fluctuating flows did not occur during the sensitive breeding or larval rearing periods of resources, their effects could not be determined directly. In addition, fluctuating flows were concentrated in the final year of study when much of the field research had been completed.

Steady flows of less than 10,000 cfs occurred for only 4 percent of the study period. Analysis of the effects of low flows required historical photography, review of literature, and extrapolation to assess their impacts. For example, low flows were shown to increase the number of backwaters available as rearing habitat for native fishes. However, the number of backwaters was only surveyed at two flows, 5,600 and 28,000 cfs. Additional surveys and an understanding of how fluctuating flows affect backwater formation will help refine this modified operating plan.

Short Study Period

A major constraint and source of uncertainty in the operational scenarios (Figures B-4 through B-8) is that they are based on findings from a short, three-year data collection period. Long-term predictions can be extrapolated from short-term findings if the assumptions are accurate and studies are designed to measure aspects of the ecology of a resource that are important in the long-term.

One of the major assumptions of the riparian research is that the abundance and diversity of wildlife populations depends on the areal extent, species diversity, and structural heterogeneity of riparian vegetation. The short-term impact of floods is a direct loss in areal extent of vegetation. A loss in area of vegetation could decrease population sizes for some wildlife species. Long-term changes in the species composition and structure of vegetation, however, may be more important to wildlife diversity than actual areal extent of vegetation. The disturbance caused by very infrequent flooding could play an important role in maintaining diverse and structurally heterogeneous riparian vegetation.

Flooding has a negative effect on most resources and cannot be recommended as a management tool unless the long-term effects of flooding on the species composition of vegetation and other resources are understood. The short-term findings of this study on the effects of flooding on biological resources are not sufficient to allow for recommendations regarding the duration, frequency, and magnitude of future flooding, if such events are even necessary.

Lack of Comparative Pre-Flood Data

Prior to the GCES, few broad scale biological studies had been conducted in the Grand Canyon. The lack of quantitative biological information prior to the filling of Lake Powell and subsequent flooding of the river limited the comparative value of data collected during flood flows. This limited our ability to assess the effects of flooding for some resources.

Additional Information Needed

Additional information will continually be required to refine and verify the modified operational scenarios for each resource. As future monitoring and research confirm or refute the seasonal flows recommended, the link between dam operations and biological impacts will become clearer. A concerted effort to fill the uncertainties and gaps in data through research and monitoring will assure that any operational changes made at the dam will be absolutely necessary for the long-term protection of downstream resources.

SECTION X: RECOMMENDATIONS FOR FUTURE RESEARCH AND MONITORING

This research effort identified a need for additional information to refine the operational critera for all biological resources. An ongoing program to monitor selected biological resources is recommended during the next few years of dam operation. The need for this program is based on a recognition of the potential changes to biological resources which could occur as a result of changes in dam operations.

Riparian and riverine ecosystems are inherently dynamic. They are adapted to high levels of disturbance from natural flooding and seasonal droughts. Predicting how a changing river system will respond to management actions is difficult. Monitoring will provide the means to follow the effectiveness of management actions and determine long-term patterns of change.

Development of a research and monitoring plan will fulfill several objectives: (1) determine the response of resources to specific flows that were not studied but are expected to occur in continuing dam operations, or are called for in the modified operating scenarios; (2) improve our ability to predict long-term biological changes by monitoring ecosystem responses to management actions or natural perturbations; and (3) use information from the monitoring program to further refine operational criteria, if necessary, in an ongoing process of interactive management.

Recommended operating criteria may change over time as new data are collected. The modified operating scenarios for biological resources presented in this report rely on data gathered over a time frame of three to five years. Therefore, the scenarios are based on the short-term response of resources to dam operations. However, the impacts of new operating criteria on resources must be evaluated in the long-term as well. Monitoring provides a mechanism to track the short- and long-term responses of resources to modified and current operations. Operational changes can be used to test hypotheses on how critical resources will respond to different flows.

Aquatic Community

Many unresolved questions remain concerning the effects of dam operations on aquatic resources. The effects of low and fluctuating flows on successful reproduction of humpback chub in the Little Colorado River need to be determined. In particular, the role that fluctuating flows play in drift of eggs and larvae into the cold mainstem river needs to be understood. The effects of fluctuating flows on juvenile humpback chub in back-water habitats should be investigated during the time of year when they are most susceptible to adverse conditions in the mainstem. The factors that restrict humpback chub reproduction to the Little Colorado River need to be determined to understand why humpback chub do not use other tributaries. The possibility that warming the river will expand the reproductive range of humpack chub, but contribute to the spread of exotic fish predators and competitors, also needs to be examined.

The low summer flows called for in the scenario for common native fishes may be refined by censusing the number of backwaters at several flow levels preceded by both steady and fluctuating flows to determine what combination of conditions increase the number of available backwaters. Both the number and quality of backwaters are important to native fish. Understanding how backwaters differ ecologically from one another and which types of backwaters are preferred by fish will lead to a further refinement of those flows necessary to improve native fish habitat.

Changes in the trout food base, food availability, and feeding rates should be monitored to determine if fluctuations affect the fish foodbase over the long-term and increase trout growth rates. Gravel bars used for trout spawning under low flows should be identified and surveyed in order to identify the minimum flow necessary to inundate the bars and maintain natural reproduction as well as the incremental loss of spawning area as flows drop below the prescribed minimum.

The ecological advantages and disadvantages of increasing river water temperature by means of a multi-level intake structure need to be identified. Investigation of the limnology of Lake Powell and Lake Mead is important in both understanding the character of the river and in assessing potential impacts to water quality and fish food resources which could result from increased water temperature. Preliminary laboratory and field studies of temperature tolerances for native and exotic fishes will give an indication of the value and potential problems of increased water temperature on the fish community.

Terrestrial Riparian Community

The scenario for vegetation and wildlife is based on the short-term response of vegetation to flooding, and changes in vegetated area resulting from peak flows. An important assumption of this scenario is that increases in the extent of riparian vegetation will lead to increased wildlife populations. However, other characteristics of vegetation may have important effects on wildlife diversity and community structure. These other important characteristics include patchiness, species diversity, and structural diversity. Predicting changes in species composition and diversity of vegetation under different flows is more difficult than predicting changes in area. Therefore, a program to monitor patterns of seedling establishment and colonization in open areas will give an understanding of how vegetation structure and diversity respond to dam operations. The dominant vegetation of the riparian zone is long-lived and relatively slow-growing, and the effects of flows may take several years to become visible. Only continued monitoring of vegetation can provide an understanding of long-term change.

The response of riparian wildlife to changes in vegetation is difficult to predict over the long-term. Monitoring indicator species gives an understanding of how wildlife may respond to cumulative vegetation changes. Riparian nesting birds are an excellent indicator group for vegetation change since they rapidly adjust to changing aspects of vegetation such as density, species composition, structural diversity, and productivity. Monitoring riparian bird densities, habitat use, nesting behavior, and species diversity will give an understanding of how long-term changes in vegetation affect wildlife.

Rare species of special interest such as willow flycatcher and river otter should be monitored to determine if their populations and distributions are declining or expanding under current and modified operations. In addition, rare and restricted habitats such as marshes should be monitored to determine whether they will recover from scouring floods, and what effects their loss or recovery will have on the animal species that use them.

Insects are an important link in the food chain for most terrestrial vertebrates and they have not been studied in detail along the river. Emergent aquatic insects are a major energetic link between the aquatic and terrestrial ecosystems, since they have aquatic juvenile life stages and move as adults into riparian vegetation. These insects provide a large part of the food resource for birds, lizards, and other animals. The extremely high bird and lizard densities found along the river may in part be attributed to this supplemental food source. Operations, especially fluctuating flows, could have strong impacts on insect productivity and species composition. In turn, changing insect productivity is likely to affect the density and productivity of insectivorous terrestrial vertebrates. Monitoring changes in insect species composition, abundance, and emergence patterns at different flow levels will lead to useful predictions of how dam operations affect the terrestrial food base. Studies of indicator species such as birds will illustrate the relationship between insect productivity and vertebrate productivity.

SECTION XI: CONCLUSIONS

Floods Adversely Affect Terrestrial Biological Resources and to a Lesser Extent the Aquatic Resources

Recurrent flooding of the downstream riverine system has major adverse impacts on terrestrial vegetation, the beaches and sediment which support its growth, and the terrestrial animals which inhabit it. Vegetation is lost through scouring, burial, and prolonged inundation. Recovery of the riparian ecosystem depends on the long-term maintenance of suitable substrate which will support continued vegetative growth.

Aquatic resources are, in general, adversely affected by floods which limit available nursery areas for trout and the common native fishes. The major beneficial effect of floods occurs at the mouth of the Little Colorado River when high mainstem flows increase the area of low-velocity spawning and nursery habitat for humpback chub.

Fluctuating Flows Have Direct Effects on Aquatic Biological Resources and Indirect Effects on Terrestrial Resources

Daily changes in river flow of greater than 10,000 cfs adversely affect the rearing areas of both common native and exotic fishes. Effects of fluctuating flows on humpback chub reproduction in the Little Colorado River and on growth and survivorship of juveniles in the mainstem could not be determined due to the limited availability and timing of fluctuations. Fluctuating flows may benefit trout growth by making drift organisms more available, but they can also result in stranding of fishes, loss of natural reproduction, and potential problems in the maintenance of food resource populations.

Fluctuating flows decrease the areal extent of vegetation over baseloaded steady flows. However, in general the effects of fluctuating flows on the terrestrial system are indirect. For example, loss of aquatic insect production through fluctuating flows could reduce food availability for some terrestrial vertebrates.

Increase in Maximum Flow Under The Uprate and Rewind Program Will Decrease the Areal Extent of Vegetation and Could Decrease Population Sizes of Wildlife

Areal extent of vegetation will decrease as a result of increased maximum flow, but species composition of vegetation should not change. No wildlife species will be lost as a result of the flow stage caused by the Uprate and Rewind Program, but population sizes could be decreased.

Effects of the Program on aquatic resources depend, in large part, on changes in amplitude of fluctuation, the rate of change from high to low water, and any change in duration of high and low flows. Any change beyond that which presently occurs would need to be evaluated once specific operation schedules are proposed.

Dam Operations Can Be Modified to Benefit Biological Resources

Operational alternatives have been identified which could minimize adverse impacts to biological resources. All beneficial operational alternatives eliminate flooding. The operational scenario for combined biological resources favors aquatic resources over terrestrial resources because the aquatic system is more directly affected by flows.

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RECREATION REPORT

Appendix C

KOLBS
"EDITH"
4 MILES BELOW BASS CAMP
MILE 112

Emery Kolb with the broken boat "Edith," Christmas Eve, 1911, four miles below Bass Camp, Colorado River Mile 112. Photo courtesy of the Emery Kolb Collection, Northern Arizona University, Flagstaff, Arizona.

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SECTION I: INTRODUCTION AND MAJOR FINDINGS

This appendix summarizes the various studies conducted as part of the recreation component of the Glen Canyon Environmental Studies (GCES). Two questions were addressed by the recreation studies:

(1) Do dam operations significantly affect recreation downstream from Glen Canyon Dam? Specifically, do dam operations affect the quality and safety of three types of recreation: fishing on the Colorado River in Glen Canyon National Recreation Area; day-use raft trips in Glen Canyon, and white-water boating in Grand Canyon National Park?

(2) Does the potential exist to operate the dam differently to enhance or protect the quality and safety of recreation?

Both of these questions have been answered affirmatively. Dam operations do affect downstream recreation, and there are ways to reduce adverse impacts.

In this chapter we first describe the recreational groups affected by dam operations and the management actions to be evaluated, and then summarize our major findings.

It should be emphasized at the outset that this entire appendix takes a recreational perspective. Obviously, many goals other than recreation must be considered in managing a facility like Glen Canyon Dam and Powerplant. This appendix discusses what we have learned about recreational quality and safety in isolation from the much more complex problem of balancing recreational goals against the many goals that must ultimately be considered.

Recreational Groups

Within the study area, three groups account for almost all of the recreational use of the river. We will refer to these groups as Glen Canyon anglers, Glen Canyon day-use rafters, and Grand Canyon white-water boaters.

<u>Glen Canyon anglers.</u> Following completion of Glen Canyon Dam, the first 15 miles between the dam and Lees

Ferry were stocked with trout and became an excellent cold-water fishery. This section of the river is flat water and is fished predominately from boats which are launched at Lees Ferry. Bank fishing is also done in the area around Lees Ferry.

The Glen Canyon fishery has rightly been called a "blue-ribbon" trout fishery. It combines the opportunity to catch large rainbow and other trout with the spectacular scenery of Glen Canyon. Judging from the number of large fish (over 600 millimeters) caught, the fishery peaked in 1978. Due to increased fishing pressure, average weight of fish caught declined between 1978 and 1984 but has since increased somewhat. Usage peaked in 1983 at 52,000 angler-days.

Based on a survey of anglers conducted as part of the GCES, it was estimated that anglers average about 5.3 angler-days per year at Lees Ferry. This implies that about 10,000 people fished there in 1983. Since 1983, participation has dropped steadily in response both to poorer fishing and to more restrictive fishing regulations implemented in 1978 and 1980 (Janisch 1985). In 1985, the area recorded only 15,000 angler-days. In 1986, Arizona Department of Game and Fish (AGF) enacted a lures-only regulation.

Trout fishing does occur downstream in Grand Canyon, but it is a relatively minor activity at present in terms of user-days and was not included in the present study.

<u>Glen Canyon day-use rafters.</u> In 1985, 8,469 visitors took half-day commercial raft trips on the 15-mile flat-water section of the Colorado River between the dam and Lees Ferry. At flow levels less than powerplant capacity (31,500 cubic feet per second [cfs]), the 20-person tours depart from a dock near the dam and float down to Lees Ferry. When releases are made above powerplant capacity, trips depart from Lees Ferry with 10 passengers and motor part way upstream before floating back downstream.

<u>Grand Canyon white-water boaters.</u> The Grand Canyon white-water section of the Colorado River begins at Lees Ferry and continues for over 200 miles through Grand Canyon National Park. It is one of the premier white-water rafting areas in the world because of the numerous challenging rapids and the magnificent natural setting in one of the longest stretches of remote backcountry in the United States. White-water

enthusiasts come from around the world to run this stretch of the Colorado.

From 1960 to 1972, the number of boaters annually running the river grew from 205 persons to 16,432. The rapid growth of white-water boating in Grand Canyon was paralleled by a dramatic increase nationwide. (During the period 1960-1983, white-water boating experienced one of the fastest growth rates of all major outdoor recreational activities [U.S. Department of Interior 1983].) In 1972, increasing problems with the management of human waste and trash along the river, damage to fragile soils and vegetation, and destruction of prehistoric sites prompted the National Park Service (NPS) to regulate river use more closely. The NPS established a ceiling on the number of user days allowed each year and instituted stricter river-use regulations to help minimize impacts by river runners.

For the past five years the NPS has limited total white-water user-days to 115,500 per year for passengers on trips provided by commercial outfitters and 54,450 user-days per year for private individuals. In 1985, approximately 85 percent of the white-water boaters took trips with commercial outfitters and 15 percent as part of private trips. Commercial trips are organized by boating companies that conduct tours for paying customers. Partly as a result of the flow regulation of Glen Canyon Dam, this has grown into a $14 million a year industry according to NPS records. Currently, approximately 20 companies have contracts from the NPS to conduct commercial trips. Private trips are organized and conducted by individuals who supply their own equipment, supplies, and boating skills. Demand for private trips far exceeds the allowed visitation, as is evidenced by the 5-year waiting list to obtain a permit for a private trip during preferred seasons.

Many types of boats are used to run the Grand Canyon. The most common are small 14- to 18-foot oar-powered rafts (roughly 45 percent), motorized 30-foot rafts (25 percent), kayaks (20 percent), and dories (6 percent).

The motorized rafts, holding 25 to 30 people, are run almost exclusively by commercial guides. Motorized trips vary from a 3- to 4-day trip between Lees Ferry and Phantom Ranch (approximately 90 river miles), to a 7- to 10-day trip through the entire Grand Canyon to Lake Mead (approximately 250 river miles).

Non-motorized trips can be either privately or commercially guided, and vary in length from 12 days to almost 3 weeks. Non-motorized rafting is permitted throughout the year. Motorized trips are permitted from mid-December through mid-September.

During their passage through the canyon, white-water boaters camp each night along the river. The much-preferred locations for camping are the beaches along the margins of the river. Sandbars provide relatively level campsites free of vegetation and rocks. Sandbars are also utilized for daytime stops when the shade from riparian vegetation can provide very welcome protection during the summer. Various attraction sites such as the inhabited village at Havasu, prehistoric Indian ruins, and wilderness side canyons add much to the recreational experience. Between stops at camping and attraction sites are the famous rapids interspersed with peaceful flat-water sections.

Figure C-1 shows a typical distribution of visitation over the year 1985 for white-water boaters and Glen Canyon anglers. White-water boating peaks in the summer. During the months of June, July, and August, 67 percent of the trips occur. When May and September trips are included, 92 percent of the trips are accounted for. Figure C-1 also indicates that 86 percent of the fishing in 1985 occurred outside the three-month summer period. These patterns are typical. Day-use rafting, like white-water boating, is concentrated in the three summer months.

Management Actions Evaluated

For purposes of this report, two dimensions of dam management will be evaluated: (1) the **average daily flow** released from the dam, measured in cubic feet per second (cfs), and (2) the extent to which dam releases are **steady or fluctuating**.

Average daily flows can vary greatly. Flows as low as 1,000 cfs are technically feasible and are experienced on rare occasions. Powerplant operations can involve flows up to 31,500 cfs. The river outlet works combined with full powerplant operations can increase flows to around 48,500 cfs. Use of the spillways as well could push the flow well over 200,000 cfs, although such high flows are very rare. The recreation studies examined how alternative average daily dam releases affected recreation quality and

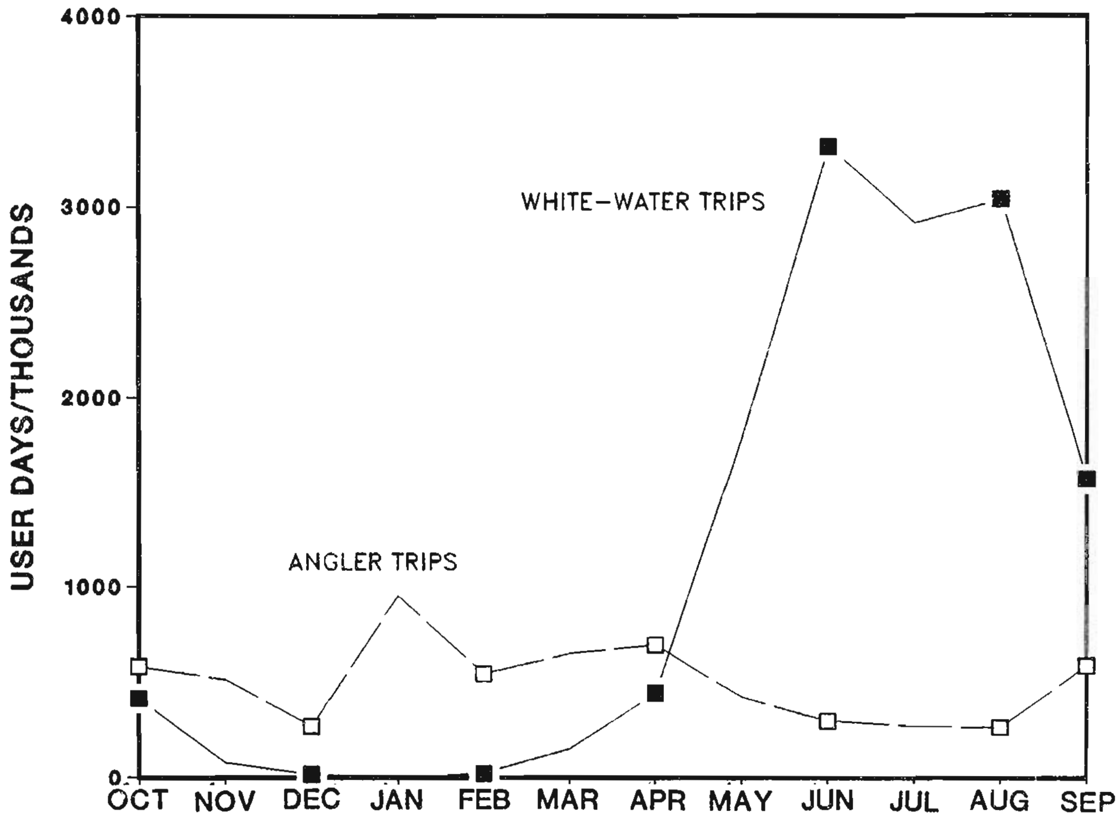

Figure C-1. Recreation use by month for 1985.

safety. For example, white-water accident rates are higher during flood flows (>31,500 cfs) than during moderate flows (9,000 cfs to 16,000 cfs). Low flows (<9,000 cfs) leave larger camping beaches exposed for use by white-water boaters. Moderate flows are perceived by anglers to improve their chances of success.

Recreational effects were found to depend not only on the average daily flow, but also on whether dam releases are relatively steady throughout the day or fluctuate widely. For purposes of the recreation studies, **steady flows** were defined as all flow release patterns where the difference between the minimum and maximum release rates at the dam during a 24-hour day was less than 10,000 cfs. **Fluctuating flows** were defined as all flow patterns where the daily difference between the minimum and maximum releases was 10,000 cfs or more.

These definitions are based on responses of recreationists and river guides to survey questions. Questions were asked regarding the level of fluctuations that were perceptible and tolerable. When changes in flows exceed 10,000 cfs on a daily basis, fluctuations are perceptible by a substantial majority of recreationists, and, therefore, this becomes the logical definition of fluctuating flow for this appendix. When asked the largest daily fluctuation that would be "tolerable," a majority of commercial white-water guides and private white-water trip leaders stated fluctuations of less than 10,000 cfs. Of course, such survey responses are subjective and may be more indicative of preferred flows than of the maximum fluctuations that could actually be tolerated. Still, the relatively small fluctuations reported in response to this question do represent real concerns. For example, fluctuations can leave a white-water raft that was floating when moored the night before stranded on rocks or sand in the morning and make planning trip itineraries more difficult.

The relationships between dam releases and recreational quality and safety will be explored in more detail later on. Before looking at the recreation studies in more depth, the principal findings will be summarized.

Major Findings

- The highest quality white-water boating occurs at relatively high constant flows of 29,000 to 33,000 cfs. Such flows provide an exciting ride and navigable conditions for almost all rapids, and fast enough boat speed to allow boaters time for hikes and visits to special canyon sites. Constant flows in the neighborhood of 10,000 cfs are ideal for fishing. This flow level is sufficient to allow boat access to all sections of Glen Canyon, but not so high as to make boat handling and safety a problem, or to disperse fish populations and reduce catch rate.

  The apparent conflict between these two groups is not as serious as it seems at first glance because white-water boating is concentrated in the summer months while much of the fishing occurs in the winter (see Figure C-1).

  Recreational quality was measured in terms of recreation benefits received--the maximum amount that recreationists would be willing to pay per trip over and above actual expenditures. Departing from preferred flows has a substantial adverse impact when quantified in this way. For example, commercial white-water boating passengers receive benefits of nearly $900 per trip ($115 per day) when flows are constant at 33,000 cfs, but only about $300 per trip ($38 per day) when flows are 10,000 cfs. Anglers average $126 per trip ($50 per day) in benefits at 10,000 cfs, but only $60 per trip ($24 per day) at a constant flow of 3,000 cfs.

- A major long-run concern of white-water boaters is the potential loss of beaches in the Grand Canyon due to the erosive effects of flood flows and the fact that the supply of beach sediment has been greatly reduced by the presence of Glen Canyon Dam. If the number and size of beaches in the Canyon were greatly reduced, the benefits from white-water boating would be reduced by approximately 50 percent. This is because beaches provide the most desirable campsites for boaters, and support the riverside vegetation and wildlife which otherwise would be scarce. In 1985, for example, estimated white-water boating benefits would have been $5.2 million lower if beaches had been substantially less available.

- Except for low average daily flows, fluctuations are detrimental to both white-water boating and fishing as compared to constant flows at the same average daily flow. Fluctuations impair an important aspect of the experience for white-water boaters--the naturalness of the setting. Fluctuations make the management of white-water trips difficult and create undesirable fishing conditions. The presence of fluctuations can reduce the benefits from white-water boating and fishing trips by $800,000 per year (15 percent) compared to benefits that would be received at the same average daily flows, but in the absence of fluctuations.

- Flow impacts on recreational safety closely parallel impacts on quality. Three sources of data were used: estimates of the risk of white-water boating accidents at various flow levels provided by white-water guides, NPS accident records, and observation data at major rapids gathered by the GCES researchers. While flow level affects the risk of boating accidents (primarily significant equipment damage) for anglers in Glen Canyon, the overall accident rate is extremely low: approximately 1 per 1000 boat-days (Underhill, Hoffman, and Borkan 1987). The safest flow levels are between 10,000 and 16,000 cfs, with the greatest risk of accidents between 16,000 and 31,500 cfs.

  Overall, the risk of serious (incapacitating) injury from white-water boating is very low. The NPS accident records from 1981-1983 indicate that the probability of serious injury is 0.005 per boat run through the Grand Canyon. The observation data from 1985 and 1986 give similar, but not directly comparable results, since these data indicate the risk associated with running each of ten serious rapids in the Grand Canyon, not the risk from an entire trip. These data indicate that the risk of any injury from running a boat through a serious rapid is 0.001. The risk of a serious injury is 0.0004.

  The NPS accident records do not show an overall relationship between accident rate and river flow level, except at Crystal Rapid, where a significantly greater number of injuries occurred at flood flows. There was also a nonsignificant trend toward a greater number of injuries at low flows at Horn Creek Rapid.

The GCES observation data, which addressed a wider range of both minor and serious injuries, equipment damage, and measures taken to avoid risk, found that the safest flow range overall is 16,000 to 31,500 cfs. Many indicators of risk increased both at higher flows and lower flows. The rate of flipping boats and injury is statistically higher at higher flows. For example, the chance of flipping a boat in a major rapid increases from 2 percent at low and medium flows to 8 percent at flood flows. The chances of falling overboard also increase, but do not reach statistical significance. Hitting rocks is significantly more frequent at low flows, increasing from 2 percent at high and flood flows to 9 percent at medium and 13 percent at low flows. Thus the chances for equipment damage seem greater at low flows while the risk of personal injury seems to increase at higher flows, particularly flood flows.

The increased risk to personal safety at flood flows prompts boaters to increasingly avoid serious rapids under these conditions. For example, at flood flows (above 31,500 cfs), 45 percent of passengers walk around Crystal Rapid, more than twice the number that walk at high and medium flows.

- Fluctuations in flow, as distinct from particular flow levels, do not appear to affect the safety of white-water boating. However, for fishing from boats in Glen Canyon, the picture is less clear. Resource managers believe that fluctuations play a role in some kinds of accidents. However, the limited statistical studies to date have not found a relationship between fluctuations and accidents. This is an area needing more study.

- Avoiding very low (<5,000 cfs) and flood (>33,000 cfs) releases and avoiding large daily fluctuations can produce substantial improvements in recreational quality and safety under a wide range of yearly runoff conditions.

  This conclusion follows from comparisons of actual operations to operations that would come closer to producing ideal conditions from a recreational perspective. Both a low-water year (1982) and two high-water years (1984 and 1986) were analyzed (see Section IV). Such comparisons indicated that recreation benefits would increase by as much as $2 million per year (and possibly more) and that safer conditions would simultaneously be created.

- When monetary benefits are compared across recreational groups, white-water boating tends to outweigh fishing even in some non-summer months when fishing activity is relatively high. This is partly the result of large benefits per trip for white-water boating and the sensitivity of boating values to changes in flows. However, it is also due partly to the reduced quality and quantity of fishing in recent years. Our analysis indicates that rehabilitation of the fishery could triple total annual benefits from the fishery and thereby give fishing increased relative weight when compared with white-water boating.

- Dam operations affect the quality of Glen Canyon day-use raft tours only when flows rise above 46,000 cfs. At higher flows, the commercial operator does not offer the trip due to the cost of fuel required to get upstream. Safety of these tours is not affected by flow levels of less than 46,000 cfs or by fluctuations.

Report Organization

Section II describes the studies performed as part of the recreation component of GCES. These abstracts are intended to help the reader better understand and interpret the study findings. They cannot, however, substitute for the comprehensive descriptions found in the referenced technical reports that were completed for the individual studies summarized here. Section II does summarize how recreational quality and safety were measured.

Section III reports the findings of the studies. The chapter is organized around the three recreational groups described above, detailing how each group is affected by average daily flows and whether the flow is constant or fluctuating. Long-term effects are also considered.

Section IV begins by examining the potential recreation benefits that could be produced through modification of dam operations, specifically by: (1) avoiding very low and very high discharges, (2) by avoiding fluctuations, and (3) by creating optimal flow conditions for recreation. The recreation conditions resulting from actual dam operations in 1982, 1984, and 1986--years which represent a wide range of reservoir inflow conditions--are compared to the recreation conditions that would have occurred in the same years had recreationally-orientated modifications in operations been instituted.

The total benefits that would be lost if substantial numbers of beaches were eroded away are also estimated in Section IV. Next, the five scenarios that would enhance specific environmental resources--as presented in Section VII of the GCES Final Report are evaluated from a recreational perspective. Then, two management actions that could affect recreation are discussed: continued rehabilitation of the Glen Canyon fishery and changing the intake structure in Glen Canyon Dam to raise the temperature of the water released from Lake Powell.

Section V summarizes the conclusions and recommendations of the recreation studies and suggests additional work that would be helpful in addressing the impacts of current operations and possible modifications.

SECTION II: MEASURING RECREATIONAL QUALITY AND SAFETY

The recreational component of the GCES involved several separate, but coordinated studies. A total of five technical reports were produced. These are listed in Table C-1, including authors and titles for the reports and the organizations and agencies that were involved in the day-to-day research activities. The first two studies focused on quality while the remaining three dealt with safety.

While the analysis presented in this appendix depended to some extent on all five technical reports, results from Bishop et al. (1987) and Brown and Hahn (1987) will receive particular emphasis. These results will be drawn on extensively to explain how quality and safety were defined and measured.

Table C-1. Technical Reports from recreational component, Glen Canyon Environmental Studies.

Title	Authors	Organizations and Agencies Performing Research
Glen Canyon Dam Releases and Downstream Recreation: An Analysis of User Preference and Economic Values.	Richard C. Bishop, Kevin J. Boyle, Michael P. Welsh, Robert M. Baumgartner, and Pamela R. Rathbun	HBRS (Consulting Firm), Madison, WI.
Simulating the Effect of Dam Releases on Grand Canyon River Trips.	Ronald E. Borkan and A. Heaton Underhill	Cooperative National Park Resources Study Unit, Tucson, AZ.
An Analysis of Recorded Colorado River Boating Accidents in Glen Canyon for 1980, 1982, and 1984 and in Grand Canyon 1981-1983.	A. Heaton Underhill, Michael H. Hoffman, and Ronald E. Borkan	Cooperative National Park Resources Study Unit, Tucson, AZ.
The Effects of Flows in the Colorado River on Reported and Observed Accidents in Grand Canyon.	Curtis A. Brown and Martha G. Hahn	Bureau of Reclamation and National Park Service.
Boating Accidents at Lees Ferry: A Boater Survey and Analysis of Accident Reports.	Lawrence Belli and Robert Pilk	National Park Service.

How Quality Impacts Were Measured

Measuring the impacts of river flows on recreational quality involved data from three main sources: (1) surveys of and informal contacts with guides and private trip leaders; (2) attribute surveys of white-water boaters, Glen Canyon anglers, and day-use rafters; and (3) contingent valuation surveys of these three user groups.

Over 300 commercial white-water guides and private trip leaders were surveyed by mail to identify the impacts of different steady and fluctuating flows on commercial and private trips and the actions they take to mitigate those impacts. The guides described the effects of flows in terms of scouting rapids, walking passengers around rapids, the risk of accidents in rapids, time spent on the river each day, changes in the trip itinerary, selection of campsites and mooring locations, minimum and maximum safe flow levels, and the optimal flow levels for trips. Fishing and day-use rafting guides were contacted informally to gain their insights about the effects of flows on quality and safety.

The attribute surveys were conducted to identify which aspects of each activity recreationists found important. These attributes, such as the amount of time rafters have to explore side canyons, represent the pathway by which dam operations may affect the value of the recreation experience. Attribute survey results were combined with results from the White-Water Guide Survey and informal discussions with resource managers and fishing and day-use rafting guides to identify which important attributes are affected by river flows. The flow-sensitive attributes identified for each group are shown in Table C-2. This table shows only those attributes that are sensitive to flows. Many other attributes important to recreation were identified during the attribute surveys. Good weather is an example of an important positive attribute that does not depend on flows and thus is not included in Table C-2. As the table demonstrates, many important attributes are flow sensitive.

The attribute survey results were used to design the contingent valuation surveys. The goal of these surveys was to assess the quality of recreation under different river flows.

Table C-2. Flow sensitive attributes.

Glen Canyon Anglers	Glen Canyon Day-Use Rafters	Grand Canyon White-Water Boaters
Catching trophy fish	Point of departure	Being in natural setting
Catching fish		Stopping at attraction sites
Access up-river		Running big rapids
Boat problems/damage		Walking around rapids
		Camping beach size and availability

The contingent valuation method, as applied in these surveys, involves asking recreationists the maximum amount they would pay, beyond their actual expenses, for access to recreational opportunities. This amount is called the "surplus value" or, in more technical terms, "consumer surplus."

In the contingent valuation surveys, over 1,000 recreationists were asked to report the surplus values for their actual trips. They were then asked to assess how the quality of recreation would change under different dam operating scenarios. Written scenarios were prepared that described the recreation conditions in terms of the flow sensitive attributes and how those attributes would be affected by dam operations. White-water scenarios were based upon the simulation model (Borkan and Underhill 1987) which projected changes in trip characteristics at various flows, and upon the experience of river guides and boaters. Fishing guides and anglers helped develop the fishing scenarios. Table C-3 shows one scenario describing fishing at a steady flow of 3,000 cfs, and another scenario describing white-water boating at an average daily flow of 22,000 cfs, with releases fluctuating from 10,000 cfs to 31,500 cfs.

Table C-3. Scenarios describing two flow conditions.

Fishing at a Steady Flow of 3,000 cfs

Boat anglers have said that getting upstream to fish can sometimes be a problem at low water (3,000 cfs or less). At a constant flow of 3,000 cfs, large boats cannot get past the sand and gravel bar three miles upstream from Lees Ferry, while even very small boats may have to be dragged over slippery rock gravel bars. Consequently, nearly all of the fishing would occur in the three miles just above Lees Ferry. In addition, damage to boats and motors is somewhat more frequent than at higher water levels. However, low water tends to concentrate fish, and bank anglers can find large areas of exposed gravel and rocks, leaving a great deal of space between the water and the edge of the vegetation.

White-Water Boating with an Average Flow of 22,000 cfs with Fluctuations

With large daily fluctuations from 10,000 cfs to 31,500 cfs, around an average daily flow of 22,000 cfs, most people are aware of water level changes. The boatmen will have to take more care in selecting mooring and camping sites. Due to low water levels in the morning, gear may have to be carried (perhaps across rocky areas) to be loaded on the boats. Boatmen may decide to wait above certain rapids for the water level to rise or may have to hurry to get to a certain rapid before the water level falls. In addition, some rapids may be difficult due to exposed rocks at low water levels and other rapids might be quite large at high water levels, and it is likely that passengers may have to walk around a few of the rapids. When the water is high or rising, however, the standing waves in some of the major rapids become larger, resulting in a bigger "roller coaster" ride.

Scenarios like those in Table C-3 were constructed to describe a wide range of flow conditions, as listed in Table C-4. For example, the third scenario for the Glen Canyon anglers describes fishing conditions when the average daily flow is 3,000 cfs, but flow levels fluctuate during each 24-hour period between 1,000 and 15,000 cfs.

Table C-4. Flow conditions (both actual trip flows and hypothetical flow scenarios) evaluated by each group.

Glen Canyon Anglers	Glen Canyon Day-Use Rafters	Grand Canyon White-Water Boaters
Actual trip	Actual trip	Actual trip
Flow steady at 3,000 cfs		Flow steady at 5,000 cfs
3,000 cfs with fluctuations daily		5,000 cfs with fluctuations daily
Steady 10,000 cfs		Steady 13,000 cfs*
10,000 cfs with fluctuations daily		Steady 22,000 cfs
Steady 25,000 cfs		22,000 cfs with fluctuations
25,000 cfs with daily fluctuations		Steady 40,000 cfs
Steady 40,000 cfs		Reduction in beaches
Double chance for a trophy size fish		
Double chance of not catching fish		

* No 13,000 cfs scenario with fluctuations was included for white-water boaters because it was impossible to word a scenario that sounded sufficiently different from the 22,000 cfs with fluctuations scenario to justify including it as a separate question.

Some other special scenarios focusing on potential long-term environmental effects of dam operations were included. For anglers, scenarios were added that described fishing conditions under which the chances of catching a trophy fish were doubled and conditions under which the chances of not catching any fish ("getting skunked") were doubled. For white-water boaters, a special scenario was added describing the recreation experience if substantial numbers of beaches in the Grand Canyon were lost.

In the case of the Glen Canyon day-use rafters, for which the only flow sensitive attribute was whether the trip departed from the dam or Lees Ferry, the only condition evaluated was their actual trip. For purposes of analysis, these respondents were then broken into two groups, depending on departure point. The outcome of applying the contingent valuation technique, then, was a surplus value for the trip actually taken and for each of the alternative trip scenarios. These values were estimated for all three user groups. The results were used to develop functions showing how the surplus value of the recreation experience changes as flow conditions change.

Dollar Measure of User Preference

Dollar values are used in everyday life to communicate relative importance. When we read, for example, that videotape recorders have become a billion dollar a year industry, this tells us something about how important these devices have become to consumers, and hence, to the industry and employees who produce them. In a sense, such dollar values convey something about the priority that our society is placing on the item being valued. Similarly, dollar values can be used to evaluate social priorities in natural resource management.

By definition, resource management involves choices among alternatives. This is certainly true when choosing appropriate flow release patterns from Glen Canyon Dam. As discussed in Section I, a wide variety of daily and annual flow release patterns are technically feasible within the constraints set by the design features of the dam, the inflows of water from upstream, and legal and administrative requirements. Each potential flow release alternative has its own implications for power revenues; the well-being of terrestrial and aquatic ecosystems downstream; various recreational users of Lake Powell, Glen Canyon, and the Grand Canyon; water levels at Lake Mead; and the legal requirements for operation of the dam. Decisions about release patterns, thus, involve a complex balancing of many social priorities.

Such priorities are usually based, at least in part, on the preferences of user groups. But, how are such preferences to be measured? One approach would be simply to ask users which alternatives they would prefer. This was done in the current study as part of the attribute surveys. Nevertheless, using a dollar yardstick to quantify preferences has significant advantages over simple ranking of alternatives.

First, dollars are a commonly used and easily understood unit of measure. To say, for example, that Grand Canyon white-water boaters prefer flow Alternative A to flow Alternative B is certainly relevant information, but more information is communicated by saying that white-water boaters gain $100,000 more per year in benefits under Alternative A than they do under Alternative B. Dollars take on extra significance in an absolute sense because we measure the worth of so many things in monetary units. This is true for not only mundane things like bus rides or a can of beans, but for objects of art, classical music recordings, tickets to the Super Bowl, and vacations in exotic places.

The second advantage of using dollars to measure preferences is that they are easily added, subtracted, and compared. Other more qualitative measures of preferences are not easily reduced to a common denominator. Resource managers must inevitably work with aggregates of people. When a given dam release alternative affects both white-water boaters and Glen Canyon anglers, the dollar benefits accruing to each group can be added to measure the aggregate impact of that alternative. Perhaps more importantly, when user groups disagree, dollar values provide a basis for comparison. We can determine which alternative produces the largest total dollar benefits for each group separately or for all groups combined.

While the GCES did not involve a full benefit-cost analysis of alternative regimes for operating Glen Canyon Dam, dollar valuation of recreational effects was conducted in full accordance with accepted practices for benefit-cost analysis. Surplus value is the accepted measure of economic value in the Economic and Environment Principles and Guidelines for Water and Related Land Resources Implementation Studies (U.S. Water Resources Council 1983) and applies not only to recreation but to other project purposes such as municipal and industrial water supply, waterway transportation, agricultural production, and flood control. Furthermore, the Principles and Guidelines specifically endorse contingent valuation as an acceptable technique for measuring recreation benefits. A review of recent research literature from natural resource economics, conducted as part of the recreation component of the GCES, indicated that this endorsement of contingent valuation is further justified by recent advances (Bishop et al. 1987). Nevertheless, it is important to view dollar measures in perspective.

Dollar Measures in Perspective

To the extent that flows affect the quality of downstream recreation, those effects will be reflected in recreational values. More favorable flow conditions will produce higher values than less favorable conditions. However, it is important to recognize that recreational values will also reflect many other influences, including current and past policies. For example, the values generated by white-water boating each year are directly affected by NPS policies such as those governing total recreational use of the Grand Canyon and launch schedules. Likewise, the recreational values generated by Glen Canyon fishing are tightly linked to fishery management decisions of the AGF. To fully understand the economics of Colorado River recreation and the potential effects of an entire range of policy alternatives would have taken us far beyond the goals of the GCES. The dollar valuation of the downstream effects of dam operations on recreation was conducted holding all other management policies constant.

In addition, it should be explicitly recognized that only specific, rather unique forms of recreation were studied here. Results are not generalizable to other forms of recreation or to other locations. For example, fishing values generated, say, below Flaming Gorge Dam or on rivers in the Pacific Northwest could be substantially different from the values estimated here. Furthermore, many activities other than white-water boating occur in Grand Canyon National Park, and the values reported here for white-water boating would not apply to sight-seeing, hiking, or other activities in the Park.

How Safety Impacts Were Measured

Theoretically, safety could have been treated as a part of quality. One attribute of a recreational trip could have been its relative safety. However, it was decided at the outset of the GCES that safety should be treated separately. This decision was motivated partly by recognition that the effects of dam operations on safety were a recurring concern expressed in the public debate leading to the GCES. Also, all

The analysis of NPS accident records was based on the small number of accidents that were serious enough to be reported. This meant that the data base was quite small. The observation study was conducted to provide a larger data base from which to assess the relationship between river flow levels and a wider range of white-water boating accidents, incidents, and risk management actions. Observers were placed in the Grand Canyon at ten rapids, at intervals between August 1985 and September 1986. They observed nearly 5,000 boats running rapids. Both steady flows and fluctuating flows were present during the observation periods. The observers recorded whether each boat:

(1) Lost control of an oar

(2) Flipped

(3) Struck a rock

(4) Lost persons overboard, and if so, length of time overboard

(5) Had passengers sustaining injury and, if so, nature of most serious injury

(6) Had equipment lost or damaged

(7) Had passengers walk around the rapid

(8) Portaged or lined the boat through the rapid

Resulting data were analyzed to determine whether the rate of the accidents was significantly related to actual river flow at the time. Other variables (e.g., type of boat) were also evaluated, but are not discussed here because they are not controlled as part of dam operations. (See Brown and Hahn 1987.)

Summary

In summary, impacts on recreational quality were assessed by:

- Identifying which aspects or attributes of the experience were important to recreationists. For example, taking hikes in side canyons is very important to white-water boaters.

- Understanding how dam operations and resulting flows affect these aspects of the recreation experience.

For example, low-water releases make raft trips travel more slowly, reducing hiking time available.

- Measuring how the dollar value of the experience would change for recreationists as a function of different dam operations. For example, the value boaters placed on the white-water experience might be significantly diminished if the opportunity for taking side canyon hikes was reduced.

Impacts on the safety of recreation were assessed by:

- Obtaining expert opinion on the effects of dam operations on recreational safety. For example, white-water guides believe that it is unsafe to run motor rafts with passengers at flows less than 8,000 cfs.

- Evaluating official NPS accident records to identify any relationship between recorded accidents and river flows.

- Observing white-water boats running rapids at various flows to correlate safety with flow levels and/or fluctuations.

SECTION III: RESULTS

In this chapter, we summarize the impacts of flows on the Grand Canyon white-water boating experience, the Glen Canyon fishing experience, and the Glen Canyon day-use rafting experience. The chapter draws heavily on the GCES technical reports by Bishop et al. (1987); Underhill, Hoffman, and Borkan (1987); and Brown and Hahn (1987). The reader interested in additional details should consult these reports. Results for recreational quality will be stated in terms of dollar benefits per trip. Safety impacts will be described as risk rates for particular types of accidents and using overall composite risk indices. In Section IV, these results will be used to evaluate how quality and safety are affected by actual dam operations and how operations and other policies could be modified to improve recreation.

Recalling some definitions from the introductory chapter may prove helpful in understanding the results to be presented now. Impacts on quality and safety will be related to average daily flow. However, we found that quality impacts are often determined not only from the average daily flow but also from whether the flow was relatively steady around the average or fluctuated widely. To deal with degree of fluctuation, we designated flows to be steady when the daily difference between the minimum and maximum releases at the dam was less than 10,000 cfs, and fluctuating when this difference equalled or exceeded 10,000 cfs. The discussions of flow impacts on each recreational group will begin with the impacts of steady flows and then turn to fluctuating flows. Let us turn first to white-water boaters.

Grand Canyon White-Water Boating: Effects of Steady Flow Levels

<u>Recreational Quality.</u> The effect of flows on recreational quality was assessed using the contingent valuation method. Resulting surplus values varied substantially as a function of river flow.

The first step in asking white-water boaters about their surplus values was to ask them about actual expenditures. On average, commercial white-water passengers reported expenditures of roughly $1,400 for their trip, while private boaters reported roughly $500. Figure C-2 shows surplus values over and above these expenditures that they would be willing to spend

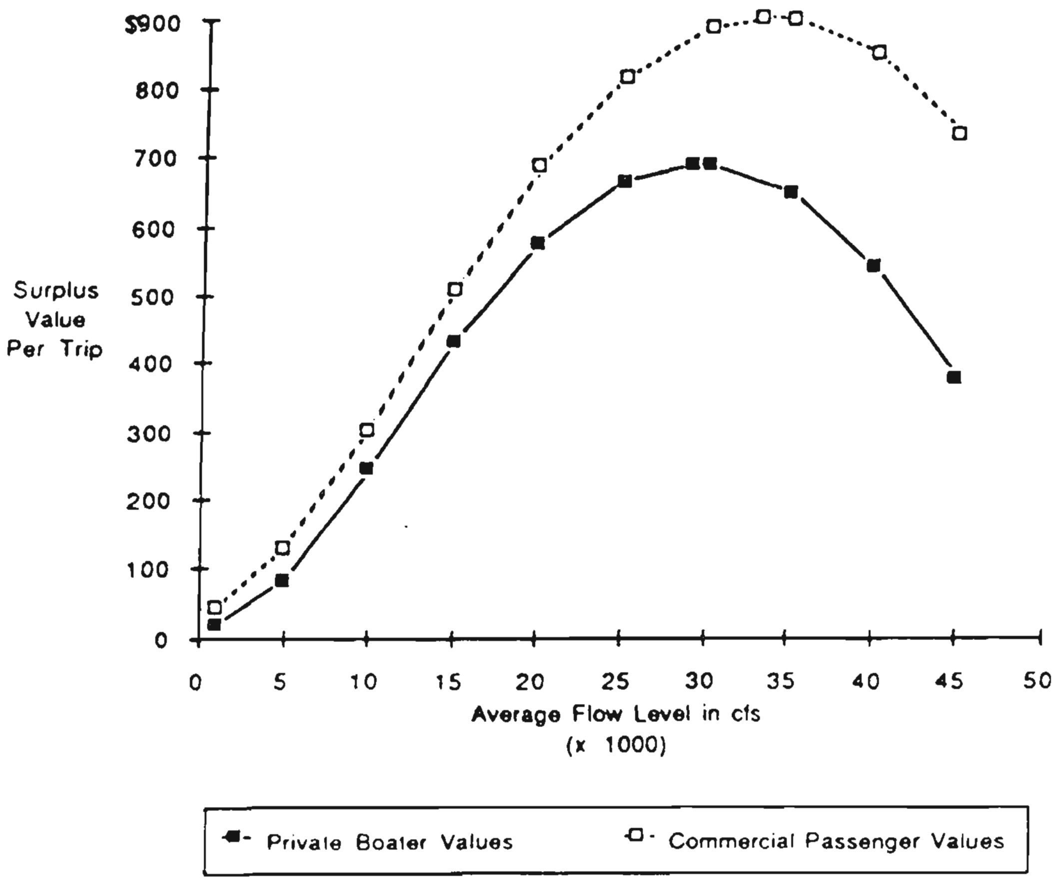

Figure C-2. White-water boating quality under steady flows: relationship between surplus values and flow levels for respondents' actual trip ($ per trip).

for access to the recreation experience at different steady flow levels. River flow level has a substantial effect on the value of the experience and the effect is similar for private boaters and commercial passengers.

The lowest surplus values are produced at very low average daily flows. For example, at 5,000 cfs, private boaters receive an average of $176 and commercial boaters $233 in surplus value per trip. This amounts to about $10 per day for private boaters and $30 per day for commercial boaters. The value of the trip rises steadily as flow levels increase. Private boaters receive maximum benefits, on average, at approximately 29,000 cfs, which results in roughly $700 in surplus value per trip ($41 per day). Commercial passengers prefer approximately 33,000 cfs, which results in roughly $900 in benefits per trip ($115 per day). Surplus values for commercial passengers were not affected by the type of boat they used. At flows above these preferred levels, the value of the experience falls off, but more rapidly for private boaters than commercial passengers.

These changes in recreational value reflect the effects of flows on important trip attributes. Time at attraction sites and for layovers depends on the speed of the current. The size and number of rapids are affected by dam releases. Boaters, particularly those on commercial trips, enjoy fairly large rapids that depend on substantial flows. At relatively low flows and flood flows, passengers, particularly those on commercial oar trips, may have to walk around rapids. This is generally considered undesirable by passengers. Flood flows may raise concerns about safety in the minds of some boaters. Some risk at rapids makes the trip more exciting, but higher flood flows (say, 40,000 cfs and above) may be perceived as too hazardous for many. The lack of crowding is important to many boaters. High and flood flows can contribute to crowding at campsites and attraction sites by inundating beaches. Both the guide survey and the attribute survey results agree closely with the contingent valuation conclusions, increasing our confidence that these results are valid.

The long-term effect of flows on the beaches in the Grand Canyon is a major concern. These beaches are critically important to white-water boaters. In many stretches of the river, they provide the only place to moor boats and camp. The beaches also support the major communities of riparian vegetation and wildlife along the river. Without the beaches, the river corridor would be a nearly shadeless, rocky landscape, with few comfortable places to camp. Wildlife, particularly bird species, would be more scarce.

To investigate the potential impact that beach losses could have, we asked contingent valuation survey participants to express surplus value for a scenario trip exactly like their actual trip except that substantially fewer beaches would be available. Table C-5 gives the exact wording of this scenario. The average commercial passenger valued this scenario at $413 in surplus value per trip ($53 per day), while the average private boater valued it at $377 per trip ($22 per day). Actual trips were valued, on average, at $829 ($106 per day) and $574 ($34 per day), respectively. Thus, under conditions experienced by our respondents, a substantial loss of beaches could reduce surplus values by about 50 percent for commercial passengers and 34 percent for private boaters.

Table C-5. Beach loss scenario wording.

<u>Beaches Reduced</u>

> There are indications that certain types of flow patterns in the long run may reduce the number of sandy beaches in the Grand Canyon. At present, the area between Hance Rapids and Havasu has fewer beaches than other parts of the canyon. Trip leaders must plan schedules very closely to ensure a good campsite in this area. As beaches disappear, this careful planning would have to be extended to other parts of the canyon.
>
> This planning might mean missing some attraction sites. Fewer beaches would increase the likelihood of camping near other parties and perhaps sharing a beach with other parties. Some camps might have to be made in areas without any sand.

Recreational Safety. The analysis of NPS boating accident records for the Grand Canyon for 1981, 1982, and 1983, suggested significantly higher accident rates at Crystal Rapid at high and flood flows, but did not show a relationship between reported accidents and river flows for the canyon as a whole. However, due to the very low frequency of accidents requiring medical evacuation, this is a fairly weak test of the relationship between flow levels and accident rates.

The accident observation study found a significant effect of flow level on several accident variables. Figure C-3 shows the variables significantly affected by flow level for the ten observed rapids taken together. For all the rapids together, the accident variables significantly related to flow are losing control of an oar, striking rocks, flipping a boat, injury, walking passengers around a rapid, and lining or portaging a boat through a rapid.

Striking rocks is most likely at low flows because more rocks are exposed. Losing control of an oar is most frequent at medium flows. Flipping a boat, injuries, walking passengers around a rapid, and portaging boats generally increase with higher flows.

These patterns are even more dramatic when Crystal Rapid is analyzed alone, as shown in Figure C-4. For this rapid, all of the above variables (except losing an oar) are significantly affected by flow, with the addition of "persons falling into the water." All variables increase with flows, except for striking rocks, which drops substantially as flows increase. A similar pattern holds for Lava Falls.

Thus, over all ten rapids observed, and for major rapids assessed separately, river flow level affects the rate of minor and significant accidents, and the actions boaters take to avoid accidents. These empirical results closely paralleled the estimates of hazard provided by white-water guides for each flow level (Bishop et al. 1987).

To determine which flow range is safest, a composite variable was constructed in which flipping a boat, losing a person overboard, a slight injury, and equipment damage were judged equally serious and received a score of 1. Hitting a rock was judged half as serious and received a score of 0.5. An incapacitating injury was judged twice as serious and given a score of 2. For example, a boat passing through

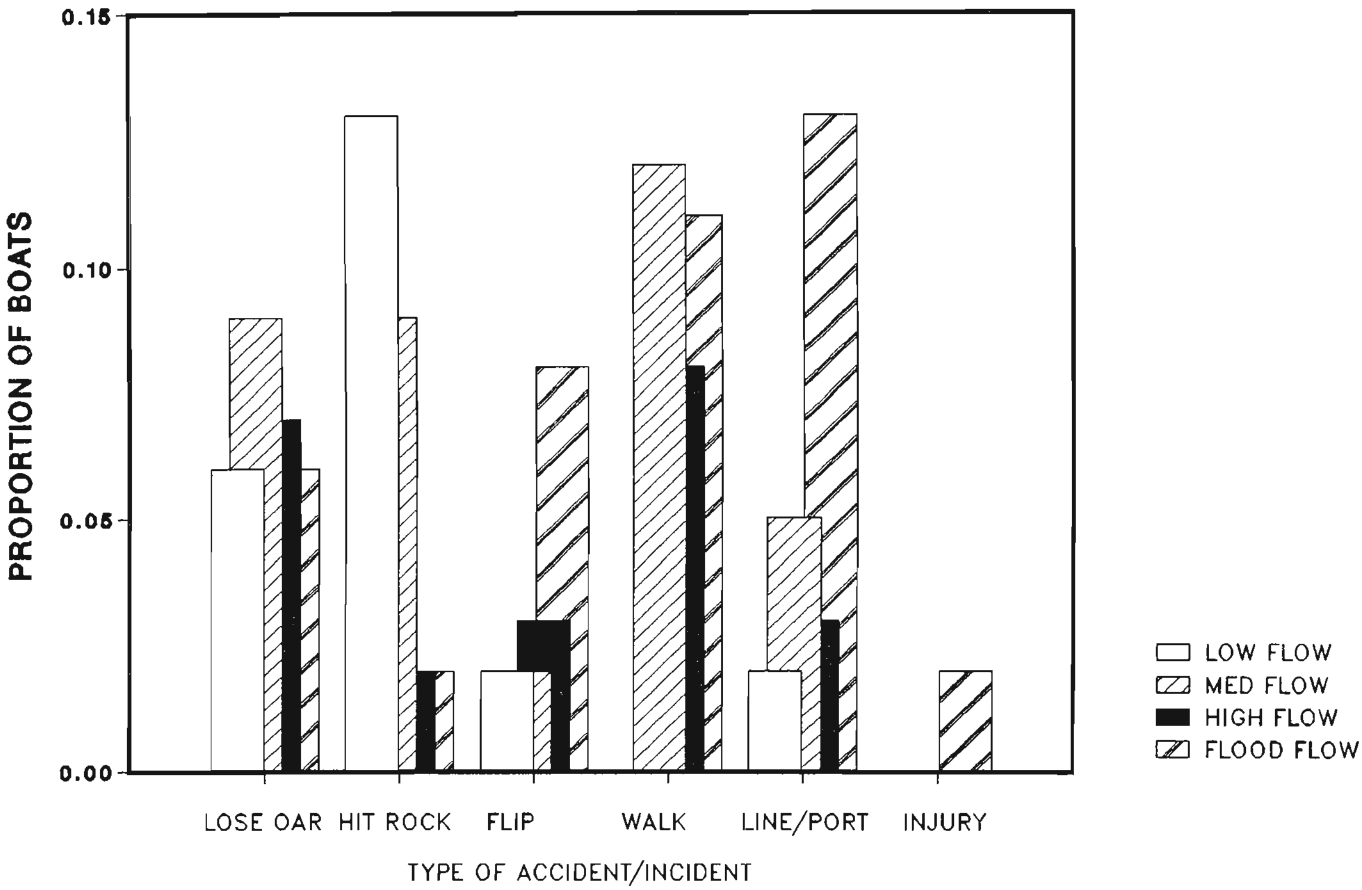

Figure C-3. Accident rates overall.

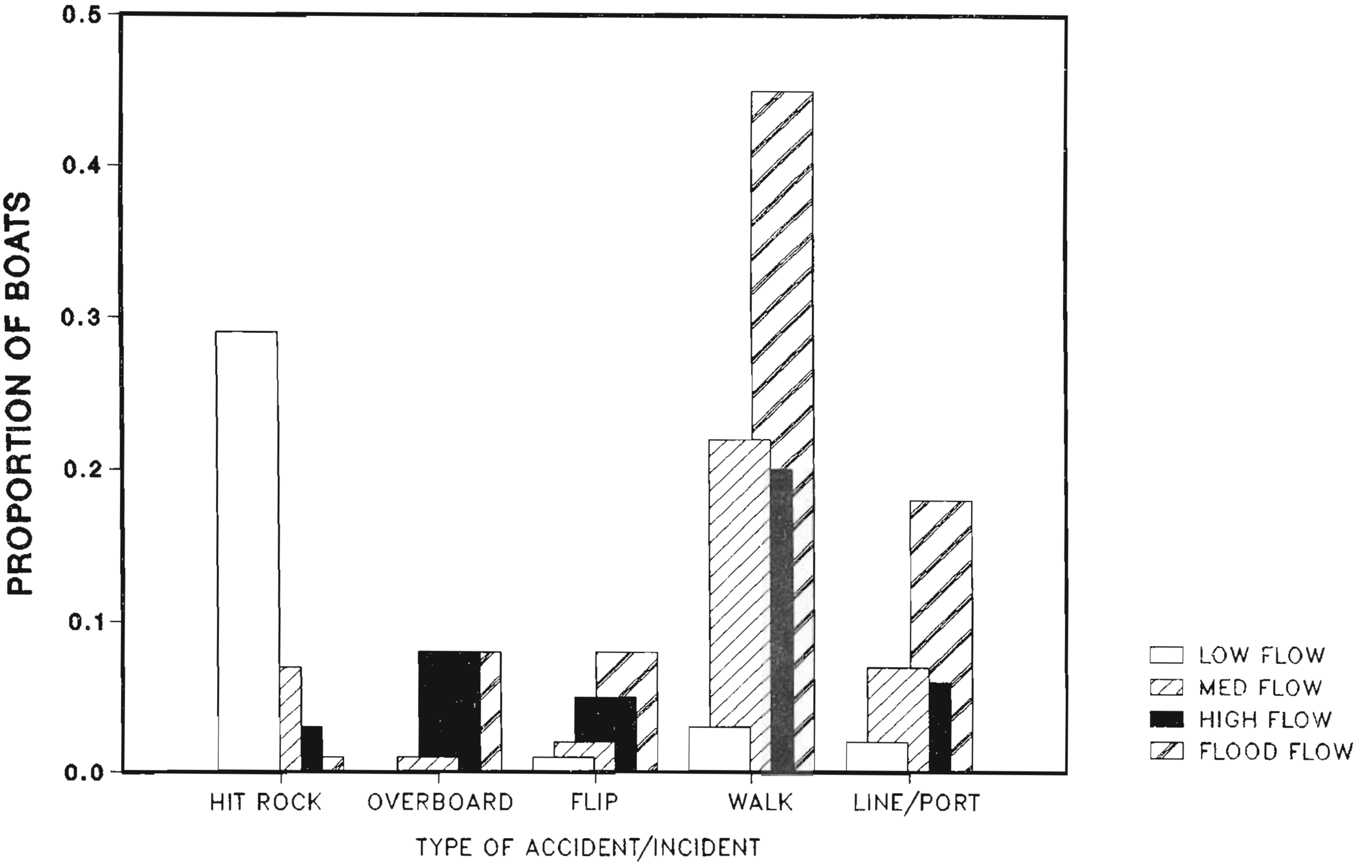

Figure C-4. Accident rates: Crystal Rapid.

a rapid without incident would receive a score of zero. A boat hitting a rock and then flipping was scored at 1.5. If a boat flipped and one passenger was seriously injured, the score would be 3. In this way, the various kinds of risks could be aggregated and compared across flow levels. While we believe this is a reasonable, if arbitrary, approach for the purposes of evaluating the aggregate hazard associated with different flow levels, other weightings could be employed. Due to the small number of observations at very low flows, the index at low flows is based on white-water guides' hazard rating (see Brown and Hahn 1987).

This index indicates that flood flows and low flows are less safe than high and medium flows when looking at all boaters combined (Table C-6).

Table C-6. Overall white-water risk index.

Flow Category	Risk Index		
	Commercial	Private	Combined
Low	.15	.25	.18
Medium	.11	.18	.14
High	.06	.17	.11
Flood	.10	.33	.22

Grand Canyon White-Water Boating: Effects of River Fluctuations

<u>Recreational quality.</u> The straight lines in Figure C-5 show the recreation benefits for fluctuating flow conditions for commercial and private boaters. These lines refer to flow conditions in which flows vary by 10,000 cfs or more around an average daily flow shown on the horizontal axis. Fluctuating flows at average daily flows in excess of 25,000 cfs and below 3,000 cfs were not evaluated, since they would not be technically feasible. In Figure C-5, the upper lines, for purposes of comparison, show the recreational value associated with steady flow conditions.

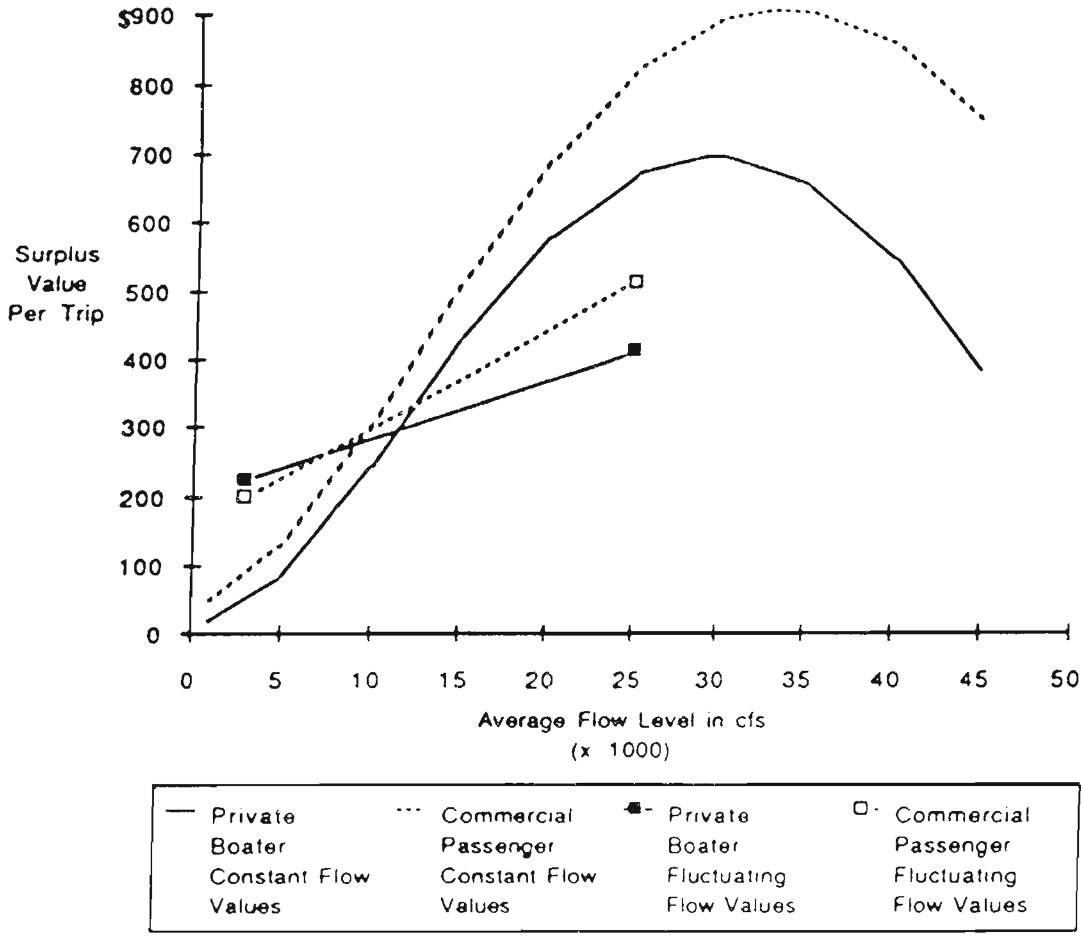

Figure C-5. White-water boating quality under fluctuating flows (steady flow curves included for comparison).

As can be seen for both private and commercial boaters, the presence of significant river fluctuations reduces the value of the experience, except at average daily flows below 10,000 cfs, where fluctuating flows are preferred to low, steady flows. Values may be lower by 25 percent or more for trips with fluctuating flows compared to steady flows at the same average daily flow.

Values are lower under fluctuating flows for several reasons. One of the primary attributes of white-water boating is experiencing the natural environment of the Grand Canyon. Perceptible fluctuations in water level make the canyon seem less natural to most participants. Allowing for changes in water level makes camping and mooring of boats for the night more difficult as well. Moored boats must be checked during the night to avoid being stranded on beaches in the morning. Fluctuations also increase the likelihood of arriving at rapids at disadvantageous times, when it may be necessary to wait for water level to change or to walk around a rapid. Careful scouting of rapids may be required. Running rapids during the low flows associated with fluctuations increases the risk that boats will get hung up on rocks. Being hung up on a rock may mean only a minor inconvenience, but can mean disaster for the trip if the boat is seriously damaged or injuries are sustained in trying to free it.

As was pointed out in examining Figure C-5, dollar values are higher for fluctuating flows around average daily flows below 10,000 cfs than for steady flows of less than 10,000 cfs. This very likely reflects a desire to have flows in excess of 10,000 cfs for at least part of each day. For example, many rapids become more passable at higher flows and the ride becomes more exciting for most passengers.

In addition to the direct impacts of fluctuations, the timing of fluctuations becomes an issue. Because the fluctuations are greatest close to the dam (they become attenuated as one moves downstream), choosing a launch time during fluctuations is important. Trips leaving Lees Ferry try to aim at specific rapids downstream during the higher end of fluctuations. For example, during such periods of fluctuations, commercial outfitters have traditionally tried to avoid the low-water days that occur on weekends. If they had to launch during the weekend, most would leave late on Sunday and make camp before reaching a rapid they felt could not be navigated at particularly low flows (below 5,000 cfs). They would then wait for the rising waters that normally occur early the following morning. Thus, good "launch windows" are reduced during fluctuating flows.

Recreational safety. The observation data allowed comparison of accident rates at high, steady flows with rates observed at high flows during fluctuations. Except for a slightly higher rate of portaging boats during fluctuations, none of the accident variables was related to fluctuations. So, while the value of the recreational experience appears significantly affected by fluctuations, we do not have evidence that fluctuations, themselves, affect safety. A more complete analysis could be done if observations at low, steady flows were available to compare to low water during fluctuations.

Glen Canyon Fishery: Effects of Steady Flow Levels

Recreational quality. The surplus values per fishing trip are depicted in Figure C-6. The solid line shows values for steady flows while the broken line applies to fluctuating flows, which will be discussed momentarily. The recreational value for fishing is low for very low flows. For example, the surplus value per trip was $60 ($24 per day) at 3,000 cfs. The value rises steadily with higher flow levels, reaching a peak of $126 ($50 per day) at 10,000 cfs constant flows. Thereafter, the value of the experience drops steadily at higher flows, declining to $64 per trip ($26 per day) for constant flows at 40,000 cfs and even lower at 45,000 cfs.

This value function reflects the combined influence of flow levels on several aspects of the fishing experience. Lower water is desirable because it concentrates the fish and is believed to produce better fishing. (Historical biological data from the Glen Canyon tend to support the conclusion that fishing is better at low to medium flows.) However, at very low water, below 3,000 cfs, it is not possible to cross the sand and gravel bar three miles upstream from Lees Ferry with motor boats, thus restricting fishing to a much smaller area. Grounding boats and striking motors on rocks is also more frequent at low flows. Thus, very low flows are undesirable.

On the other hand, high water disperses the fish, which may reduce fishing success. It also creates stronger currents, increasing problems for boat handling.

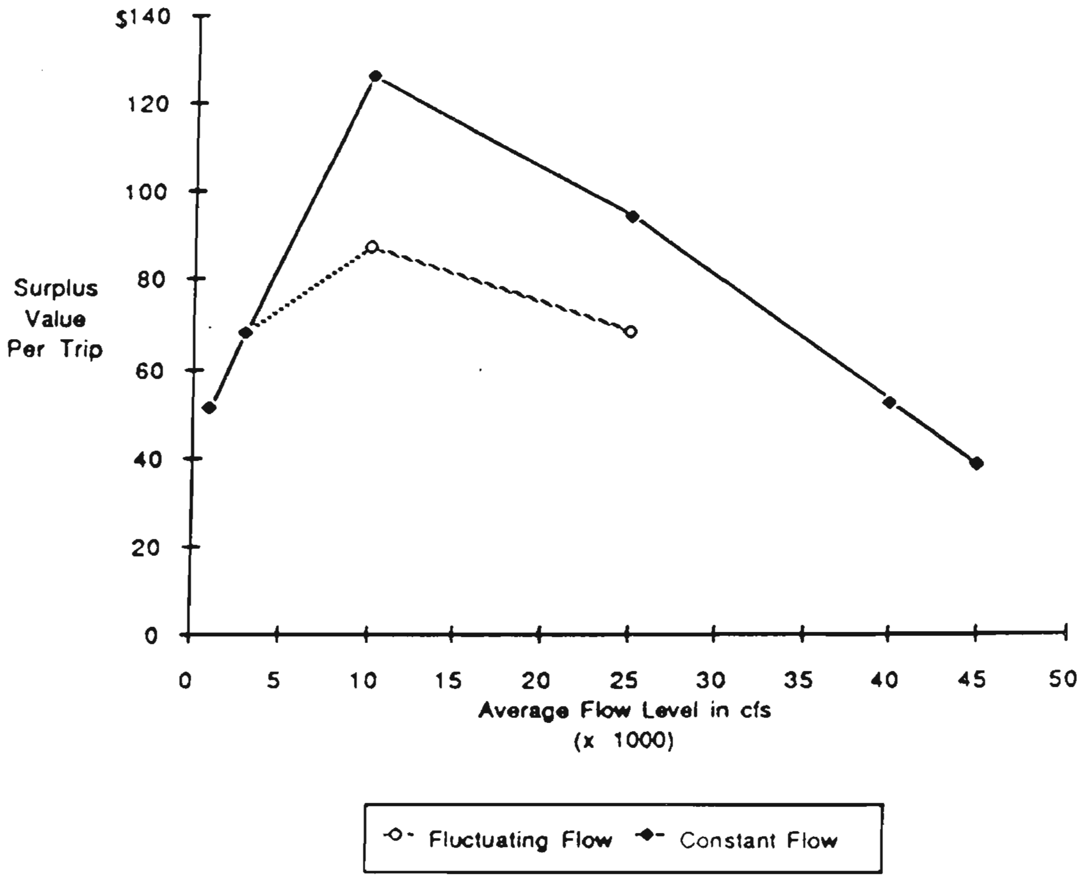

Figure C-6. Glen Canyon fishing quality.

Trade-offs among these countervailing impacts result in 10,000 cfs receiving the greatest surplus value, with fishing value declining both above and, more rapidly, below this flow level.

Recreational safety. Table C-7 shows the percent of fishing trips taken while flows were in each of the four flow ranges, for the years 1980, 1982, and 1984, and the percent of reported accidents in each flow range. An analysis of these data indicates that accidents are significantly associated with flow level, with a disproportionate number occurring at high flows. Note that while 40 percent of the trips occurred when river flows were between 16,000 and 31,500 cfs, almost 70 percent of the accidents occurred at these flows.

Table C-7. Recorded boating accidents: Glen Canyon 1980, 1982, and 1984*.

	Flow Level			
	Low	Medium	High	Flood
Percent of fishing trips	30%	25%	40%	5%
Number of recorded accidents	6	2	20	1
Percent of recorded accidents	21%	7%	69%	3%

* Based on 27,747 boat-days of fishing.

These data can be used to develop an index of the relative risk of boating accidents at the four flow levels, as shown in Table C-8. These figures were calculated based on the data presented in Table C-7 and express the probability of a reportable accident per angler-day given the average daily flow.

Table C-8. Relative risk of Glen Canyon boating accidents across flow categories.

Low	.00072
Medium	.00029
High	.00180
Flood	.00072

As can be seen, the chances of an accident are greatest at high flows and least at medium flows. Risks are approximately equivalent at low and flood flows. While no firm conclusions can be made from these data as to why high flows are associated with more accidents, stronger river currents may play an important role. It is common practice to drag an anchor while fishing to control downstream movement. At high flows it is more likely that boats will be swamped when their anchors catch on the bottom. Also, the effect of fluctuations is not separated from the effect of flow level in this analysis. Thus, the somewhat surprising decrease in risk at flood flows compared to high flows may be due to the fact that fluctuating flows do not occur at flood flows. Current data do not allow us to separate high, steady flows from high flows occurring on days when flows were fluctuating. This is a weakness that should be corrected through additional research. In the meantime, further analysis of the effects of high flows on fishing could be very misleading and will not be attempted here.

Glen Canyon Angling: Effects of River Fluctuations

Recreational quality. As has already been shown (Figure C-6), surplus values for fishing are generally lower for fluctuating than for steady flows. Fluctuating flows reduce the surplus values per trip by as much as 30 percent, except at flows of 3,000 cfs, at which both steady and fluctuating flows have the same low value.

Large fluctuations require anglers to operate part of the day at low or high flows, with the attendant disadvantages of both. Changing water levels add additional difficulties. Falling water may make it difficult to get downstream over rocks and gravel bars that had more water over them on the trip upriver. Rising water may increase the likelihood of swamping a boat while anchored or while the bow is pulled up on shore. A few anglers do favor fluctuating flows because they believe that rising water may stimulate feeding by fish. Nevertheless, the majority of anglers feel that the disadvantages of fluctuations outweigh the advantages, except at very low flows.

Recreational safety. The evidence on whether fluctuations contribute to angler boating accidents is inconclusive. NPS records of 53 boating accidents in Glen Canyon for the years 1977, 1979, 1980, 1981, 1982, 1983, and 1984 were evaluated. Sixty-one percent of the accidents involved boats flooding or capsizing. Many of the accidents occurred when boats were dragging their anchors to reduce downstream drifting.

Fluctuations in flows were identified on NPS accident records as a contributing cause in 26 percent of the cases. In surveys of boaters during April to December 1985, 18 of 21 accidents occurred during a three-month period of fluctuating flows.

The great majority of these incidents involved damage to propellers. These data suggest that rapid changes in flow level may contribute to accident rates. Further, some kinds of accidents, such as tethered boats being submerged when the river rises, are clearly related to fluctuations.

A statistical analysis was performed to explore the relationship between accidents and fluctuations in river level. The hypothesis was that an increase in flow level, which raises the river elevation, increases the chances for accidents. However, no significant differences were found in the flows from time periods containing accidents and matched "control" periods in which no accidents occurred.

From this we would conclude that river fluctuations do not appear to be a predictor of accidents. However, this type of analysis is a relatively indirect test of the relationship between fluctuations and boating accidents. As was stated at the end of the steady flow sections, we recommend that additional study be given to this issue.

Effects of Flows on Glen Canyon Day-Use Rafting

Recreational quality. The attribute survey of day-use rafters indicated that river flows affected only the point of departure for Glen Canyon raft trips. To assess whether point of departure affected the value of the trip to participants, the surplus value was determined for trips departing from Lees Ferry and trips departing from the dam. The recreation benefits measured for the two types of trips were not significantly different from one another. No significant effects of fluctuating flows were identified.

It was concluded, therefore, that river flows over a broad range do not affect the recreational quality of the day-raft trips. However, at flows above 46,000 cfs, trips become unprofitable for the rafting company, due to increased fuel usage, and are not offered. In that case, benefits of the trip are foregone in the amount of $26 in surplus value per trip (per passenger) lost.

Recreational safety. These flat water tours are extremely safe, with no reported accidents. Neither safety nor the effect of river flows on safety were identified as issues in discussions with outfitters or in the attribute survey.

Summary

Table C-9 summarizes the effects of flows on various attributes of white-water boating and Glen Canyon fishing. For each attribute, flows are listed, from best to worst. For example, beach availability for white-water boating is best at low flows and worst at flood flows. Or, looking at the bottom of Table C-9, medium flows are best for catching fish while flood flows are worst. Pluses (+) and minuses (-) indicate flows that are particularly desirable or undesirable, respectively.

As in most areas of human activity, these recreationists face trade-offs. For example, commercial white-water boaters prefer flood flows for running rapids, but low flows for beach availability. The compromise across all attributes, as expressed in surplus values, is flows on the border between high and flood flows (29,000 to 33,000 cfs). Anglers tend to be best off at medium flows in all respects, but given that a medium flow is not available, they would tend to prefer low flows for safety and catching fish, and high flows for ease of access upriver. The ideal flow for anglers is about 10,000 cfs.

While white-water boaters and anglers do disagree about ideal flows, this conflict could be partially resolved by running higher flows in the summer months when rafting peaks and lower flows during the rest of the year when most of the fishing occurs. Furthermore, both groups agree that except at low average daily flows, fluctuations detract from the recreational experience. This result was clear from the guide survey, the attribute surveys, and the contingent valuation results. The implications of these results will now be explored by evaluating dam operations modified to benefit recreation.

Table C-9. Summary of impacts on recreational resources.

	WHITE-WATER RECREATIONAL RESOURCES					
	Beach Availability	Not Walking Around Rapids	Big Ride In Rapids	Side Hikes Layovers	Naturalness of Setting	Safety
BEST	+Low	+Low	Flood	+Flood	Medium	High/Medium
	+Medium		High	+High	High	
	High		Fluctuating	Fluctuating	Flood	
	Fluctuating		Medium	Medium	Low	
WORST	-Flood	Med/Hgh/Fld	-Low	-Low	-Fluctuating	-Low/Flood

	ANGLING RECREATIONAL RESOURCES		
	Catching Fish	Ease of Access Upriver	Safety
BEST	+Medium	Medium	Medium
	Low	High	Low
	High	Flood	-High
		Fluctuating	
WORST	-Flood	-Low	*?

LEGEND
+ Significant positive impact
- Significant adverse impact
*? Effects of fluctuations across all flow groups unknown

SECTION IV: EVALUATION OF DAM OPERATION SCENARIOS

In Section III we described how current operations of Glen Canyon Dam affect the quality and safety of fishing and day-rafting in Glen Canyon and white-water boating in Grand Canyon. It was shown that the flows released from the dam can significantly affect both angling and white-water boating.

In this chapter we describe the improvements in recreational quality and safety that can be produced through changes in dam operations. Specifically, we look at the recreational effects produced by:

(1) Avoiding fluctuations in flow.

(2) Avoiding flows below 10,000 cfs (low flows) and above 31,500 cfs (flood flows). While these limits were set to improve safety, they also increase recreational surplus values.

(3) Better matching the distribution of flows during the year to the pattern of recreation use.

To better assess these changes, we have analyzed recreational effects for three water years that cover a broad range of runoff conditions--1982, 1984, and 1986. This will highlight the recreation benefits and effects on safety of operational changes under a fairly low annual release (1982 - 8.2 million acre-feet [maf]), a moderately high annual release (1986 - 16.6 maf), and a very high annual release (1984 - 20.1 maf).

For each year we calculate the total recreation benefits for anglers and white-water boaters and a measure of the risk associated with those activities. These figures are based on the actual flows released during the year. We then propose some ways of changing dam operations, assess the same measures of recreational quality and safety, and compare those to actual operations. Thus, we calculate the recreation benefits that could be obtained through changes in management under a wide range of runoff conditions.

The total recreation benefits (our measure of quality) are obtained by multiplying, for each recreational group, the surplus value of the white-water boating or fishing trip under the given set of flow conditions by the number of persons experiencing those conditions.

For all calculations, the recreation use rates for 1985 were used. This is done on a monthly basis, using the average flow conditions for that month. The resulting annual benefits for white-water boating and angling have been summed to obtain the total recreation benefits. These values can be interpreted as the total amount anglers and white-water boaters would pay in the aggregate, above their actual expenses, for the opportunity to part+icipate in the activity under the flow conditions specified.

The recreation risk indices for white-water boating are obtained in similar fashion, multiplying the risk index associated with the given monthly flows by the number of rafters for that month. These risk indices reflect the relative risk of an accident under different flow conditions, with higher values indicating higher risk. While the units of the scales are arbitrary, they are ratio scales. Thus, it is meaningful to calculate percentage changes in risk, since a zero on each scale represents zero risk of accidents. Unfortunately, risk indices could only be calculated for white-water boating. The problems with data on angling safety discussed in Section III meant that meaningful indices for fishing cannot yet be estimated.

It is important to note that the potential modifications to dam operations evaluated here have been designed to explore the implications of recreational results for dam operations. The only constraint imposed on these scenarios is that they pass through the dam the same total amount of water as was passed in the water years (WY) 1982, 1984, and 1986. Water years begin in October and end the following September. For example, WY 1982 ran from October 1, 1981, through September 30, 1982. No consideration has been given to other constraints in dam operations, such as the level of the reservoir at the start of the water year, the timing of the spring runoff, or other demands for water releases. Thus, the scenarios that develop modifications in how the dam was operated should not be viewed as proposals for actual operations. The aim is to illustrate the gains in terms of benefits and safety that would be achievable were such operational changes actually feasible. The full feasibility and desirability of operational changes are beyond the scope of the GCES.

The analysis of effects of 1982, 1984, and 1986 operations on recreation will focus on immediate short-term effects on recreationists experiencing the flows. Later in this chapter, we will turn to two possible long-run effects of dam operations: loss of beaches and rehabilitation of the Glen Canyon trophy fishery. To quantify the effects, we will compare benefits of actual operations with estimated benefits if beaches had been eroded and the fishery had been restored. The effects of five alternative dam operation scenarios designed to benefit specific environmental resources (e.g., humpback chub and other native fishes) and some non-operational alternatives will also be considered.

The Short-Term Recreation Benefits from Modified Operations

WY 1982 - 8.2 million acre-feet. The average monthly flows released in the WY 1982 are shown in the top graph of Figure C-7. The dam was operated on a peaking power (fluctuating flows) basis in all months. As is shown in the figure, this resulted in combined annual recreation benefits for anglers and white-water boaters of $4.8 million and a risk index value for white-water boaters (WW) of 13.0.

Eliminating fluctuations would increase overall recreation benefits by $0.8 million, or 16 percent. Anglers would enjoy a 42.9 percent increase in benefits ($732,000 at constant flows versus $512,000 with fluctuations). Commercial white-water boating benefits would increase by 15.9 percent, while private white-water boaters' benefits would fall slightly. The latter result is caused by flows so low in some months that private boaters would prefer fluctuating flows.

As a second step toward improving recreation for this target year, we have eliminated flows below 10,000 cfs as well as fluctuating flows, while still releasing 8.2 maf. The resulting monthly flow scenario is shown in the second graph in Figure C-7. This scenario improves recreational quality to $6.1 million in benefits, a 27 percent increase, and reduces the risk of accidents for white-water boaters by 5.4 percent, compared to actual operations.

The next modification, shown in the third graph in Figure C-7, was to shift some of the releases to better match the monthly recreation use pattern. Specifically, water is shifted away from the winter months (since fishing is the predominant activity then and anglers prefer lower flows), toward the summer months (since white-water boating predominates then and

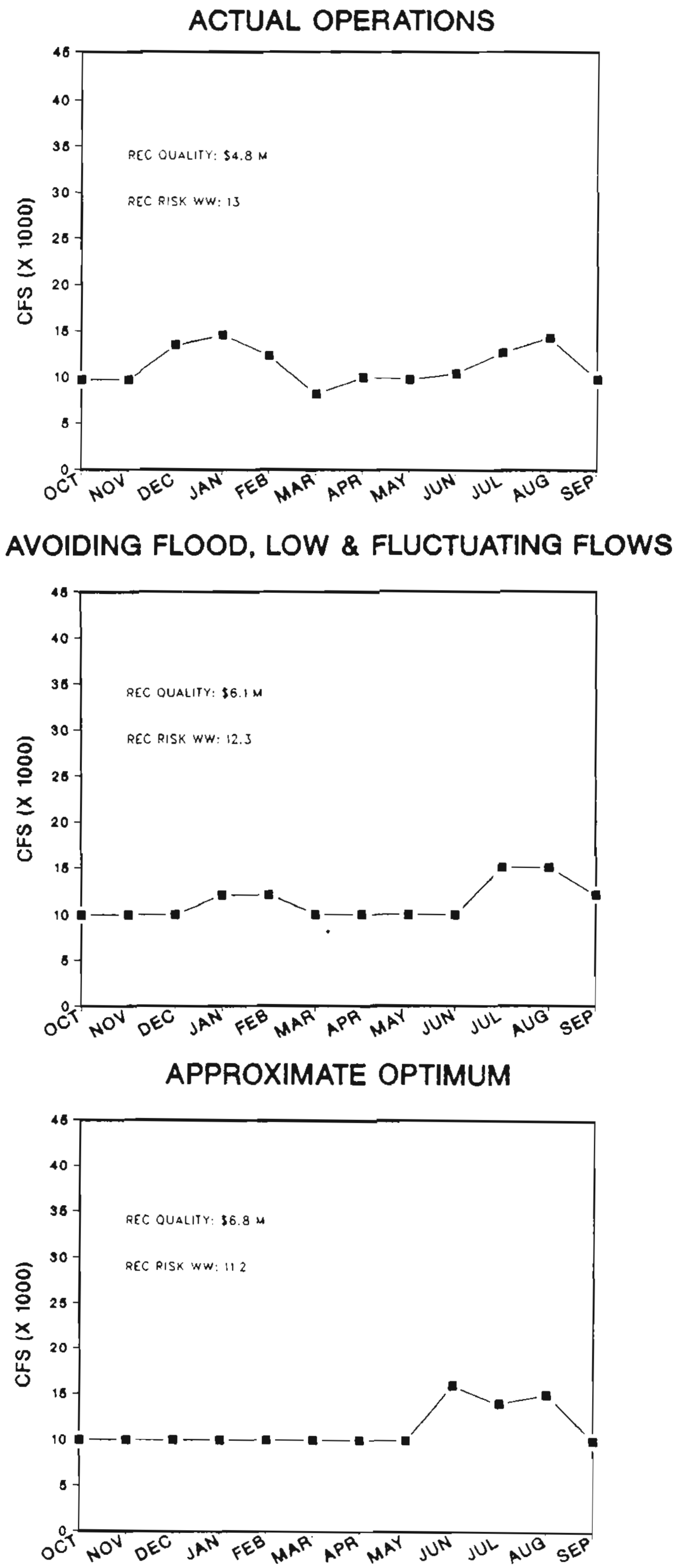

Figure C-7. 1982 water year monthly flows.

boaters prefer higher flows). This scenario, which roughly approximates the optimal flow schedule that can be produced with 8.2 maf of water, results in recreation benefits of $6.8 million (a 42 percent increase over actual 1982 conditions) and a reduction in the risk of accidents of 14 percent for white-water boaters, compared to actual operations.

WY 1986 - 16.6 million acre-feet. We next consider the WY 1986 because it is our "middle year" in terms of the annual flow--16.6 maf. Actual operations, shown in the top graph in Figure C-8, produced total recreation benefits of $10.3 million and a risk index of 10.0 for white-water boaters.

Interestingly, the increase in benefits from eliminating fluctuations in this moderately high-release year is quite close to the increase for the low-water case (1982), about $0.8 million. In 1986, this amounts to about an 8.2 percent improvement in overall recreational quality. Both anglers and white-water boaters gain benefits: fishing benefits increase by 21.8 percent, white-water commercial passenger benefits increase by 7.6 percent, and private white-water trip benefits increase by 7.0 percent. The fishing benefit increase is particularly large in percentage terms because fluctuations in WY 1986 came during October through February, all prime fishing months, whereas flows were steady during the summer months, except for July.

Eliminating flood flows, low flows, and fluctuations result in a 12 percent increase in benefits and a 20 percent reduction in white-water boating risk compared to actual operations. (See the middle graph in Figure C-8.) It should be noted that this scenario is somewhat unrealistic in the early months where flows are set at 18,000 cfs. In actuality, the high runoff in WY 1986 could not have been anticipated until forecasts began to accumulate in January. As pointed out at the outset, the goal of these scenarios is not to be fully realistic but to illustrate the implications of dam operations for recreation.

The approximate optimal scenario, in the third graph in Figure C-8, capitalizes on the opportunity to move "excess" fall flows (above the 10,000 cfs ideal for fishing) to the summer white-water boating season. This scenario reduces the risk for white-water boaters by 18 percent and boosts recreational quality by 18 percent to $12.2 million, compared to actual operations.

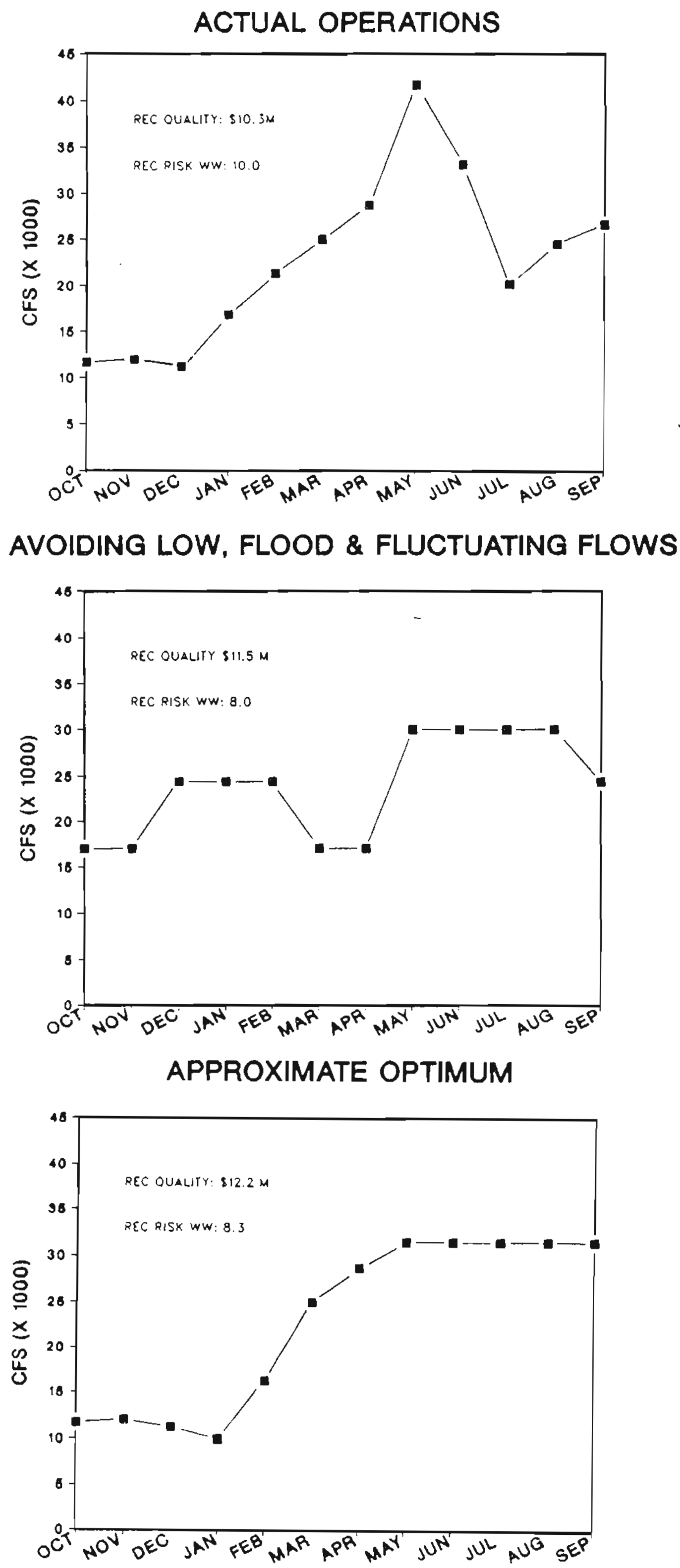

Figure C-8. 1986 water year monthly flows.

WY 1984 - 20.1 million acre-feet. This year witnessed the highest runoff in recent history. Recreation benefits from actual operations were the highest of the three years, at $11.6 million. The risk index for white-water boaters was 10.8 (Figure C-9).

The dam was run at constant flows for the entire year. Avoiding flood and low flows improves recreational quality by 4 percent and reduces white-water risk by 26 percent, compared to actual operations.

Under the approximate optimal conditions, recreational quality is increased $0.7 million (6 percent) and white-water risk is reduced 26 percent.

Possible Long-Term Impacts of Flows on Recreation

The impacts discussed so far are immediate. If flows are favorable or unfavorable to recreational quality or safety, the effects are felt directly by the recreationists on the river at the time. Flows today may also have less direct effects that will only be felt in the long run. Two possible long-run impacts will be analyzed here:

1. Potential effects on white-water boating quality of loss of beaches, and

2. Potential effects on angling quality of rehabilitation of the Glen Canyon fishery.

Beach losses. As was emphasized in Section I, beaches play an important role in white-water boating. As campsites and as places to stopover during the day, beaches along the river contribute substantially to the quality of recreation.

The problem of quantifying the potential impacts of beach loss was addressed by asking what the impact would have been in 1985 if substantially fewer beaches had been available along the river. In effect, we asked: what would 1985 white-water benefits have been if beach loss had already occurred? Table C-10 shows those calculations. The first set of figures show estimated annual benefits for actual operations and conditions in 1985. Since the sample for the contingent valuation survey was drawn from calendar year 1985 white-water boaters, the figures in this table also refer to calendar year 1985. Releases were quite high during that year, totaling 16.6 maf. Total white-water benefits were about $10.8 million. Based on

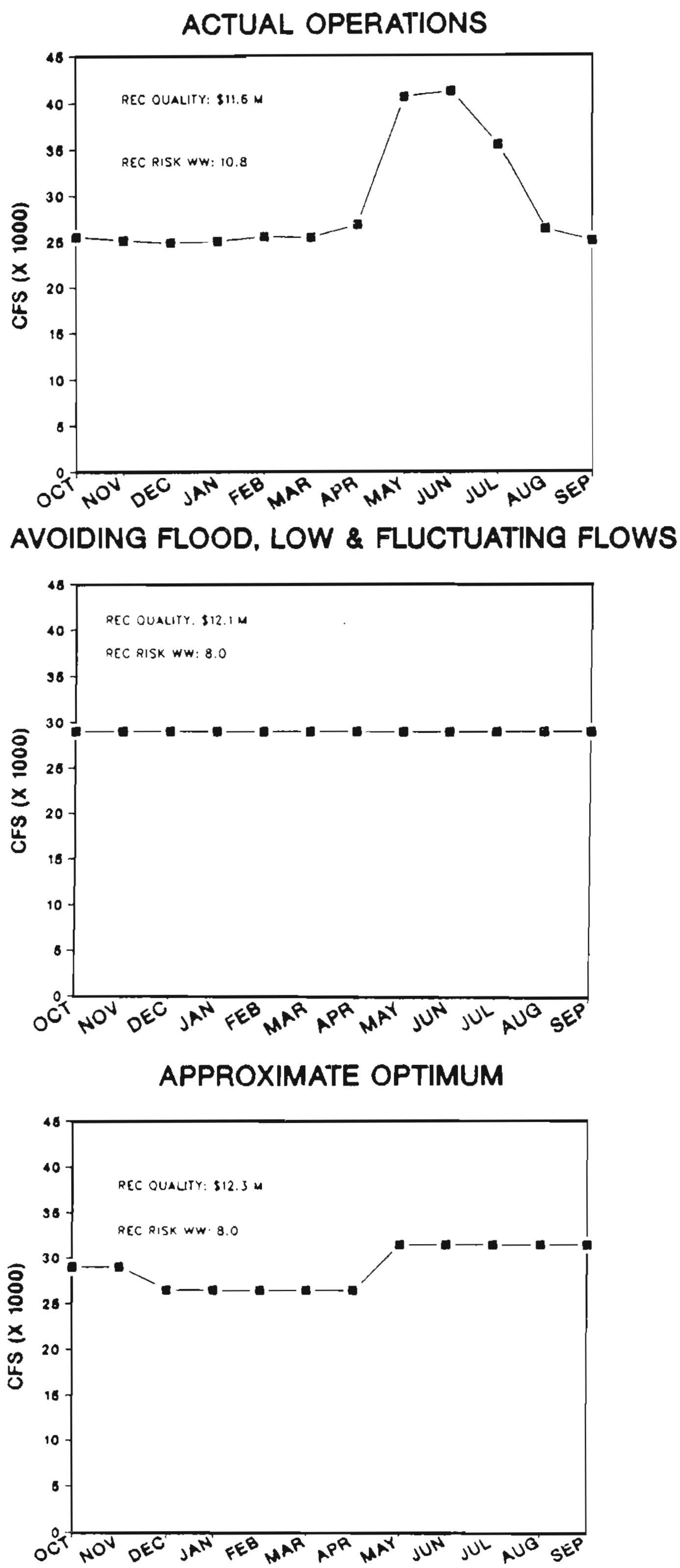

Figure C-9. 1984 water year monthly flows.

Table C-10. Effects of substantial loss of beaches on 1985 white-water boating benefits.

	Benefits/Trip (in dollars)	Total Benefits (in million $)
With Current Beaches (Actual 1985 Conditions)		
Commercial Passengers	$ 821	$ 9.3
Private Boaters	509	1.4
Total		$ 10.8*
With Fewer Beaches		
Commercial Passenger	$ 413	$ 4.7
Private Boaters	377	0.9
Total		$ 5.6
Benefits Lost to Beach Erosion		$ 5.2

* Total different from column sum due to rounding error.

beach loss scenario values as discussed in Section III, we would estimate that had substantially fewer beaches been present in 1985, the benefits would have been only about $5.6 million. This constitutes a 48 percent reduction in benefits.

Thus, we would estimate that a substantial loss of beaches could adversely affect white-water boating. Under 1985 conditions, the loss would amount to $5.2 million annually. Since 1985 was a year of relatively high water, the loss would probably be somewhat smaller in more normal years for two reasons. First, high-water years tend to provide high, steady flows during the spring and early summer. This yields larger white-water boating benefits than would occur in low-water years when medium fluctuating flows during the white-water boating season are more common. Thus, the analysis in Table C-10 began with a rather high baseline figure. Second, beaches that are flooded during high-water years are more available during low-water years. This would tend to increase the size and availability of remaining beaches.

<u>Rehabilitation of the Glen Canyon trout fishery.</u> Under all scenarios, the recreation benefits estimated for the Glen Canyon fishery are based on 1985 visitation and fishing conditions. However, as explained in Section I, both the average size of fish caught and the annual visitation were in a state of decline in 1985. Both the surplus values for fishing trips at Glen Canyon in 1985 and the 1985 visitation rates probably underestimate the recreational potential of the area. If current efforts to rehabilitate the fishery are successful, the annual number of trips may return toward previous levels and the value per trip would rise as well. Such a possibility has been considered by recalculating Glen Canyon fishery benefits based on a return to greater visitation and improved fishing quality.

The actual fishing conditions and angler visitation for 1985 produced benefits of $525,000. This corresponds to an average trip value of approximately $85 and an average value per day of $34. The contingent valuation survey indicated that each trip would have been worth $130 ($52 per angler day) if the chances of catching a trophy-size fish were doubled. If this type of improvement were achieved and participation returned to 1983 levels (52,000 angler days) in response to the improved fishing, the total recreation benefits would be approximately $2.7 million per year. The recreation benefits would have increased nearly six-fold due to a 50 percent increase in the value of each trip and a more than tripling of visitation. This estimate may provide a roughly accurate measure of the recreation benefits produced in 1983, when fishing quality was still fairly high and visitation was at a maximum. It is unlikely, however, that such a level of benefits could be sustained biologically, given the fishing pressure that such high levels of visitation would produce.

A more realistic estimate of the levels of recreation benefits that might be sustained for the Glen Canyon fishery would be based on doubling the chances of catching a trophy fish, and doubling the 1985 visitation levels. This would produce annual recreation benefits of $1.6 million. The actual benefits produced at Glen Canyon are a complex function of the fish population, flow conditions, fishing regulations, and long-term use patterns. However, this analysis suggests that substantial increases in benefits are feasible.

At present, the construction of optimal recreation scenarios is dominated by the interests of white-water boating, due to the larger population of boaters and the high per-trip values for that activity. If the value of fishing trips and/or visitation increased, more weight would be given to providing optimal flows for fishing when constructing annual flow scenarios to enhance overall recreation benefits. In this case, optimal recreation flow levels would be decreased somewhat year round, but particularly in months like April and October, when fishing is popular and white-water boating use is relatively low.

Recreational Impacts of Operational Modifications to Enhance Environmental Resources

Section VII of the Final Report explored five operational scenarios that would enhance environmental resources. Selected resources for which scenarios were developed were (1) humpback chub, (2) common native fish, (3) trout, (4) beaches, terrestrial vegetation, and wildlife, and (5) combined recreation. Each of these scenarios was evaluated for its effects on the full range of environmental resources. The purpose of this section is to explore the recreational effects of these scenarios in more detail.

Following the logic of the Final Report, we will deal with four-year cycles that include three low-water years like 1982 and one high-water year like 1986. As an index of recreational quality, the benefits of a four-year cycle will be aggregated for each plan. These benefit sums will not be discounted since our only goal is to construct an index of quality over low- and high-water years. Fishing and white-water boating will be treated separately, as they were in the Final Report itself, and in total since dollars can be added directly to give an overview of the full recreational effects.

Results for recreational quality are given in Table C-11. The baseline for purposes of comparison is the "Actual Operations" which was based on actual operations in 1982 and 1986 (see Figures C-7 through C-9). All of the scenarios improved fishing, generating at least $0.4 million in increased benefits over the four-year period. The Combined Recreation

Table C-11. Impacts of alternative scenarios on recreation (in millions of undiscounted dollars).

Plan	Fishing	White-Water Boating	Total
Actual Operations	$2.0	$22.7	$24.7
Chub	2.4	29.1	31.5
Common Native Fish	2.6	16.6	19.2
Trout	2.6	24.8	27.4
Beaches/Habitat/ Wildlife	2.7	25.7	28.4
Combined Recreation	2.9	29.3	32.2

Scenario generated $0.9 million in additional fishing benefits compared to actual operations. This is a 45 percent increase.

White-water boating is improved under all scenarios except the one designed to benefit common native fish, which has very low flows in the summer months when white-water boaters would prefer high flows. All other scenarios improve white-water boating by at least $2.1 million over four years. The Combined Recreation Scenario was designed to approach optimal conditions for white-water boating and fishing combined, and it produces $6.6 million more in white-water boating benefits than does actual operations over the four-year cycle. This is a 29 percent improvement.

Examining the last column of Table C-11 indicates that recreation benefits in total are enhanced by up to 30.3 percent by the various scenarios to enhance environmental resources. The only scenario that is worse than actual operations is the one for common native fish, for reasons that have already been explained. Also interesting are the relatively very high recreation benefits associated with the scenario for chub. This scenario involves high, steady flows that enhance white-water recreation.

The Trout Scenario raises the possibility of increasing natural trout reproduction. This could increase benefits in two ways. First, it would reduce fish management costs through reduced stocking. Second, it is commonly held that many anglers prefer to catch wild trout as opposed to stocked trout. Research on this topic is in its infancy. An interesting recent investigation is that by Johnson and Walsh (1986). Glen Canyon probably represents an intermediate case because it is sustaining some natural reproduction under current dam operations and because it is not a "put-and-take" fishery in the usual sense. In the usual put-and-take fishery, a large share of the fish are caught within a few days after stocking. Glen Canyon would more appropriately be classified as a "put-grow-and-take" fishery. Stocked fish spend long enough in the river to grow larger and to take on the characteristics of wild trout. At least part of the aversion anglers feel for stocked trout may be dissipated in the process, but more research would be required to evaluate the effects of stocking versus natural reproduction on recreational quality.

The only scenario that raises substantial safety concerns is the one designed to enhance native fishes other than chub. The low flows during a large part of the white-water boating season would increase the overall risk of accidents compared to actual operations. All the other scenarios enhance safety compared to actual operations because they eliminate floods and low flows.

It should be born in mind that only the short-term effects are considered here. To the extent that beaches and fishery productivity are affected by the various plans, these additional long-term impacts could change the conclusions.

Other Potential Management Actions

Raising the water temperature. Currently, water released through Glen Canyon Dam comes from about 230 feet below the surface of Lake Powell and is quite cold (averaging around 45 degrees F). The possibility exists of taking water from nearer the surface; water that would be considerably warmer. This has been proposed primarily to improve the downstream river habitat for the indigenous humpback chub, an endangered species which requires water temperatures above 61 degrees F for successful spawning.

Increasing the water temperature could have significant impacts on recreation, primarily white-water boating. If temperatures could be raised above 65 degrees F during the primary white-water boating season, a major benefit would be to reduce the hazard to those falling into the river. While fatalities associated with white-water boating in the Grand Canyon are rare, the five drownings which occurred from 1980 through 1985 are attributable in large part to the extremely cold water, which quickly renders persons falling overboard helpless.

Because of the very cold water temperatures, almost no one swims in the river. Warmer water would make the river an attractive place for swimming, providing a major new recreational resource for visitors. However, since increasing the water temperature would not reduce the dangerous rapids or strong currents, use of the river for swimming could be accompanied by a commensurate increase in drownings.

Warmer water (up to 70 degrees F) would make all contact with the water more tolerable, including getting soaked in rapids in the early morning or on cold days, which might extend the rafting season further into fall and early winter. Negative aspects of warmer river temperatures would include a reduction in both natural refrigeration for food and beverages and air conditioning to moderate hot summer air temperatures near the river. If river temperatures rose above 65 degrees F, some shift in the Glen Canyon fish populations away from rainbow and cutthroat trout toward brown trout might be experienced.

<u>Improved forecasting and communication of dam operations.</u> Both low, steady flows and fluctuating flows are undesirable for white-water boating. As mentioned previously, low, steady flows usually occur on weekends, when power demand is low. Boaters prefer to schedule their launches to avoid these periods. This strategy for mitigating the negative effects of low flows depends upon accurate forecasts of dam operations being available to private and commercial boaters prior to scheduling launches. Both commercial and private launches are scheduled at the beginning of the year. The potential for shifting launch dates at the last minute is quite limited for two reasons.

First, neither commercial nor private trips usually have the logistical flexibility to delay a launch. Second, since limits are set on the total number of persons launching each day, delaying a launch is permitted only if another trip has cancelled on the desired launch day. Thus, boaters can avoid less preferred flows only to the extent that they are able, when selecting their launch dates, to forecast dam operations for those dates.

Accurate knowledge of dam operations is also helpful when adjusting itineraries while on the river, especially during periods of fluctuating flows. Guides can time their arrival at critical rapids or the mooring of boats for the night to coincide with desirable flow levels only if they can predict when flow levels will change. Guides are able with a predictable schedule of fluctuations to significantly reduce many of the negative effects of fluctuations. Therefore, for both the scheduling of trips and the management of trip itineraries, accurate prediction of future dam operations and the timely communication of those forecasts to boaters can significantly enhance white-water recreation.

Summary

The analysis of short-term effects from low, moderately high, and high annual water releases (1982, 1986, and 1984, respectively) led to several conclusions. First, as has been repeatedly emphasized, recreational quality and safety respond in the same way to flows. As a general rule, flows that provide more (or fewer) benefits also provide more (or less) safety. Though more research on fishing safety is called for here, it is doubtful that such research would lead to a reversal of this conclusion.

Second, actual operations produce higher recreation benefits when more water is available to be released. Benefits produced under actual operations in 1984 and again in 1986 were more than twice that produced in the low-water year 1982, holding all else constant. The constant high flows and flood flows that normally occur in high-water years tend to provide good to excellent white-water boating conditions during spring and summer when large white-water benefits accrue. The lower benefits earned in 1982 are the direct result of medium flows during the white-water boating season. Medium flows produce lower white-water benefits per trip than high flows and flows toward the bottom end of the flood flow range. Interestingly, the risk index for white-water boating was also lower in 1984 and 1986 compared to 1982.

Third, fluctuations have a significant adverse effect on recreation benefits. In 1982, when flows fluctuated throughout the year, and in 1986 when flows fluctuated about half the year, recreation benefits were roughly $800,000 per year less than they could have been if daily fluctuations of 10,000 cfs or more could have been avoided.

Fourth, analysis of 1982, 1984, and 1986 scenarios indicates that substantial improvements in quality and safety may be achievable through modified dam operations. Eliminating fluctuations, low, and flood flows improved benefits from $0.5 (4.3 percent) to $1.3 million (27.1 percent), depending on the year examined. Modifying the release schedule to better suit the flow preferences of recreationists (i.e., the approximately optimum scenarios) led to increased benefits between $0.7 million (6.0 percent) and $2.0 million (41.7 percent) per year, compared to actual operations. And, such modifications in dam operations seem almost invariably to lead to safer conditions as well.

Potential long-term effects of dam operations on beaches and fishery productivity were also analyzed. If dam operations do lead to a long-term loss of camping beaches, the loss in recreation benefits would total millions of dollars each year. For example, had substantially fewer beaches been available in 1985, more than $5 million in benefits would have been lost even if the same number of trips had been taken. Whether by dam operations or other measures, rehabilitation of the trophy fishery in Glen Canyon could easily increase benefits by $1 million per year.

To a considerable degree, measures to protect and enhance other environmental resources such as the humpback chub would also enhance recreation. The only readily apparent exception is the low flows in summer that would enhance populations of native fish other than chub.

Raising water temperatures through a multi-level intake structure at Glen Canyon Dam and improved forecasting were also discussed. High water would have both positive and negative effects on downstream recreation. Whether the net effect would be positive or negative is impossible to say at this time.

Particularly difficult to weigh is the prospect of additional swimming opportunities against the prospect of additional drownings. Improved forecasting and communication would help moderate the adverse effects of operations on recreation, although the impact would probably not be large.

SECTION V: CONCLUSIONS AND RECOMMENDATIONS

Having already summarized the principal findings of the GCES relating to recreation (Section I), the opening section of this final chapter will be more narrowly focused. We will begin by examining the general conclusions of the GCES Final Report (as presented in Section VIII of the Final Report). The support from a recreational perspective for each conclusion will be summarized, then the limitations of the recreation studies will be explored. This will lead naturally into a discussion of future research needs.

Conclusions

- **Flood releases and fluctuating releases from Glen Canyon Dam have a significant effect on many of the downstream environmental and recreational resources.**

  The most serious potential recreational effect is probably the long-term effect of flood flows on beaches. Substantial loss of beaches would lead to white-water benefit reductions amounting to millions of dollars each year. This would constitute serious and potentially irreversible damage to a major national recreational resource.

  Except for possible damage to beaches, normal dam operations have been, to a considerable extent, conducive to white-water recreation, particularly in high-water years. Flows tend to be high (May through September) when rafting is particularly popular, and low to moderate during the good fishing months (September through April). Still, modifications in how the dam is operated could further improve recreation, particularly during low-water years. The low to medium average daily flows typical of late spring and summer in low-water years have meant lower benefits and less safety for white-water boaters than would have been achievable had more water been retained in the preceding fall and winter to be released during the heavy white-water boating months of May through September. Under current conditions such release patterns typically reduce recreation benefits by about $2 million per year in low-water years. When more water is available, this problem becomes less severe since normal procedures in high-water years call for the high flows that are preferred by white-water boaters. However, flood flows reduce safety and, particularly above 40,000 cfs, also substantially reduce white-water benefits.

Anglers are adversely affected by current operating procedures in both low- and high-water years. In low-water years, fluctuating flows tend to reduce quality and safety. In high-water years, flows tend to be more steady, but are too high to provide good to excellent fishing conditions. Typically, the loss in benefits amounts to $200,000 per year compared to what could be earned with constant flows more amenable to fishing. The risk of accidents is greater at high flows than at moderate flows.

In low- and medium-water years, normal dam operations have involved fluctuating releases necessary to generate peaking power. Such fluctuations can reduce annual recreation benefits by $800,000, compared to the benefits that could be achieved if flows were steady around similar daily averages. In fact, as our analysis of WY 1986 illustrated, fluctuations can have effects of this magnitude even in relatively high-water years. Though more research is needed, the possibility exists that fluctuations reduce the safety of Glen Canyon fishing.

Low flows, which can occur in low-water years when electricity demand is down, reduce benefits and safety for both white-water boating and Glen Canyon fishing.

Finally, restoration of the trophy fishery in Glen Canyon could increase fishing benefits by as much as $1 million per year.

- **It is possible, within the Operating Criteria, to operate during low- and high-water years in ways to prevent future degradation and in some cases enhance downstream resources.**

The recreation studies summarized in this appendix lead to the following recommendations for improving recreational quality and safety:

a. Avoid fluctuating flows unless the alternative is steady flows of 5,000 cfs or less.

b. Avoid flows of less than 10,000 cfs, especially during the main white-water boating season, April through October.

c. Avoid flows greater than 33,000 cfs whenever possible.

d. Steady flows in the range of 10,000 cfs to 16,000 cfs are desirable in the months November through March.

e. Steady flows in the range 25,000 cfs to 33,000 cfs are desirable in the months April through October.

f. Take all reasonable actions to avoid substantial loss of beaches in the Grand Canyon.

g. To the extent that it is economically feasible to do so, operate the dam so as to support a trophy fishery in Glen Canyon.

These recommendations consider only recreational objectives. This is not intended to deny the importance of many other objectives or to argue that recreation should necessarily be predominant. Our goal was to better understand the relationships between dam operations and recreation as one step toward reconciliation of the full range of objectives. We have been able to show that recreational and other environmental objectives are compatible for the most part, but to go farther would be beyond the scope of the GCES.

- **The effects of the Uprate and Rewind Program cannot be determined at this time.**

It is not possible at this time to specify precisely how the new powerplant capacity will affect future dam operations. Variability in the forecast, management options, and physical system limitations will impact the actual releases scheduled. The way that the new capacity will be used has not been formalized, and may change when future generation schedules and policies are decided.

As described in Appendix D: Dam Operations, use of the uprated capacity in the Glen Canyon generators may lead to several changes in flow patterns through the dam. These changes would be most apparent in water years with moderate inflow to Lake

Powell, which occur approximately 30 percent of the time. In these years, peak steady releases may be raised from 31,500 cfs to 33,100 cfs. During periods of fluctuation, the peak flows may also increase this amount. This would require either lowering the bottom end of fluctuations by approximately 2,000 cfs or by increasing the rate of rise and fall in the pattern of releases.

In years of high inflow to Lake Powell, which also occur approximately 30 percent of the time, the peak steady releases would likely be increased from 31,500 cfs to 33,100 cfs. Changes in the level of steady releases are not likely to affect recreation significantly.

Increases in the range or the rate of fluctuations will have a negative effect on both fishing and white-water boating. The magnitude of the adverse effects cannot be estimated until specific operational patterns are proposed.

- **Reducing the vulnerability of the endangered hump-back chub to catastrophies in the Little Colorado River watershed must depend on non-operation alternatives.**

  While this was a major conclusion of the GCES, the humpback chub is not a fishing resource and has not been dealt with in this appendix. Nevertheless, non-operational alternatives such as a multi-level intake structure at Glen Canyon Dam could affect recreation. If and when such alternatives are investigated, attention should be given to possible recreational impacts.

- **Several additional non-operational or management alternatives exist which could enhance the environmental resources downstream from Glen Canyon Dam.**

  Perhaps most promising from the standpoint of recreation would be to improve the predictability of dam operations and the communication of operational plans to recreational groups and businesses.

Uncertainties and Needs for Future Research

In the recreation studies, we have concentrated exclusively on the people who are most directly affected by dam releases: white-water boaters, anglers, and day-use rafters. The broader public may well be concerned about the long-term impacts of Glen Canyon Dam operations on Grand Canyon National Park and Glen Canyon National Recreation Area. Such concerns are sometimes dealt with under the heading of option and existence values. However, research on methods to measure such values is in its infancy and no attempt was made to estimate them as part of the GCES.

Focusing on the recreationists alone, several gaps are apparent. As noted repeatedly, the effects of fluctuations on angling safety are not yet well understood. This problem could be alleviated through further research and substantial progress might be feasible with existing data.

The observation of white-water boats running rapids proved a valuable method of measuring risks. Unfortunately, the flows during previous observation periods did not include sufficient steady flows below 9,000 cfs. Also, we lack data at some flood flows above 33,000 cfs. Observations at steady, low flows and flood flows would help complete a valuable data set that could be used to address safety issues over a full range of constant and fluctuating flows.

On the recreational quality side, further limitations and research needs can be identified. A particularly difficult problem is to predict participation in the Glen Canyon fishery under different conditions. Estimation of total benefits requires not only an estimate of the value per trip but also an estimate of the number of trips that will be taken. We know from historical experience that the number of angler-trips can fluctuate widely depending on fishing success. For this report, we speculated, based on historical experience, about how the number of trips might change if the chances of catching a trophy fish increased. A more systematic examination would be helpful.

Then, too, a major parameter has changed since 1985 when we last sampled Glen Canyon anglers. The AGF imposed a lures-only regulation for the Glen Canyon fishery. The initial impact was a rather drastic drop in participation and displacement of some bank anglers downstream. More recently, both the size of fish and the rate of participation seem to be increasing, but the data are still incomplete.

Thus, a new angler study to update the results presented here appears to be in order. Such a study would not only update the monetary values to account for changes in regulations and fish caught, but also would examine the determinants of participation in the fishery. Data may be available or obtainable to develop a participation model that would predict how participation would change in response to changes in the fishery and dam releases.

Ideally, dam flows would have been manipulated so that our contingent valuation survey respondents could have actually experienced a wide variety of steady and fluctuating flows. This was not possible, and we had to fall back on scenarios that asked respondents to imagine what their trips would have been like under different flows than they actually experienced. The scenarios were carefully constructed based on attribute survey results, surveys of white-water guides and trip leader, and informal contacts with fishing guides and resource managers. Contingent valuation questions based on scenarios produced values that were sufficiently valid to justify the analyses conducted and conclusions drawn here. However, values based on actual experiences of recreationists would be even better. As various flows are released in coming years, it would be useful to re-estimate benefits per trip as a function of flows. Since data were adequate, such a function was estimated for white-water boating under various steady flows and results were used in this report. Comparable functions for white-water boating under fluctuating flows and fishing under both steady and fluctuating flows should be substituted for results based on scenarios used in this report.

The treatment of fluctuations in the recreation studies has been intended only as a first approximation. Intuitively, the effects of fluctuating flows on recreation should be different depending on the magnitude of the fluctuation and the average daily flow around which the flows fluctuate. This supposition is supported by the results of our White-Water Guide Survey. However, as a simplifying assumption, we classified all days as either steady flow days or fluctuating flow days based on whether the difference between the daily minimum flow and the daily maximum flow exceeded 10,000 cfs without regard to the average daily flow. We believe that our simplified view provided satisfactory first approximations of the effects of fluctuations on trip values, but much room exists for refinements.

Preliminary exploration of computer models to simulate white-water boating experiences at different flows was accomplished as part of the GCES (Borkan and Underhill 1987). Through the use of the Wilderness Use Simulation Model, the effects of alternative flow regimes on white-water boating was quantified in terms of the amount of time available for attraction site visits, delays at rapids, and on congestion and crowding. These data were useful in designing the contingent valuation scenarios. For the GCES recreation component, it was decided that dollar values were the appropriate measure for recreational quality, hence the model was not utilized nor developed to its fullest extent. Future work on the model in programming, data collection, and model verification should be undertaken.

Finally, it is worth recalling that many parameters affect the quality of recreation in the Canyon. For example, NPS policies relating to launches and other aspects of white-water boating might be manipulated to increase surplus values. However, our charge in the present study was limited to an examination of the effects of flows.

In the long run, a plan for periodically sampling and surveying white-water boaters and Glen Canyon anglers should be considered. Major national resources are being managed in Glen Canyon and Grand Canyon. It is as important to build a more complete understanding of user groups and how they are changing over time as it is to build a more complete understanding of the physical and biological components of the environment. The GCES has made a beginning in this direction by including research on recreation as a full partner along with aquatic and terrestrial biology and research on sediment and hydrology. Future research on the resources of Grand Canyon National Park and Glen Canyon National Recreation Area should continue to emphasize not only the physical and biological environments, but the human dimensions as well.

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Appendix D

U. S. Geological Survey team from the 1923 Birdseye Expedition, at "Trapper's Cave." Photo courtesy of the Emery Kolb Collection, Northern Arizona University, Flagstaff, Arizona.

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SECTION I: INTRODUCTION

The Colorado River is a critical element in the lives, industry, and recreation of a large segment of the American West. It is a life-sustaining water resource that winds more than 1,400 miles through seven states and northern Mexico. The river descends from the Rocky Mountains to Mexico's Gulf of California and is the primary source of water for much of the basin it drains. The economic health, recreational opportunities, and growth potential of many communities in the basin are directly related to the management of the river. However, the flow of the Colorado River and its tributaries cannot be altered without influencing the sediment, hydrology, and the terrestrial and aquatic ecology of the riparian system. It is the objective of the Glen Canyon Environmental Studies to better understand the dynamics of this changing system as it relates to Glen Canyon Dam. An understanding of the history of the development of the river and the conflicting interests and components that define its management is necessary to understand these dynamics.

Glen Canyon Dam is the key regulatory feature on the Upper Colorado River. The objective of this report is to define the background and history of the Colorado River system, as well as the constraints and criteria that dictate the operation of Glen Canyon Dam. More specifically, it describes the operation of the dam as related to the management of the Colorado River system, the Colorado River Storage Project (CRSP), and the Western Area Power Administration (WAPA) power and transmission system.

The Colorado River (Figure D-1) has its headwaters in the mountains of Colorado, Wyoming, Utah, and New Mexico and flows southwestward to its mouth at the Gulf of California. The Colorado River drains an area of approximately 244,000 square miles (sq mi), of which 242,000 sq mi are in the United States and 2,000 sq mi are in northern Mexico. The basin extends from the Wind River Mountains in Wyoming to below the Mexican border, a straight line distance of approximately 900 miles. The basin varies in width from approximately 300 miles in the upper reaches to over 500 miles in the lower reaches. It is bounded on the north and east by the Continental Divide in the Rocky Mountains, on the west by the Wasatch Mountains, and on the southwest by the San Jacinto Mountains. Tributaries drain seven western states: Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming.

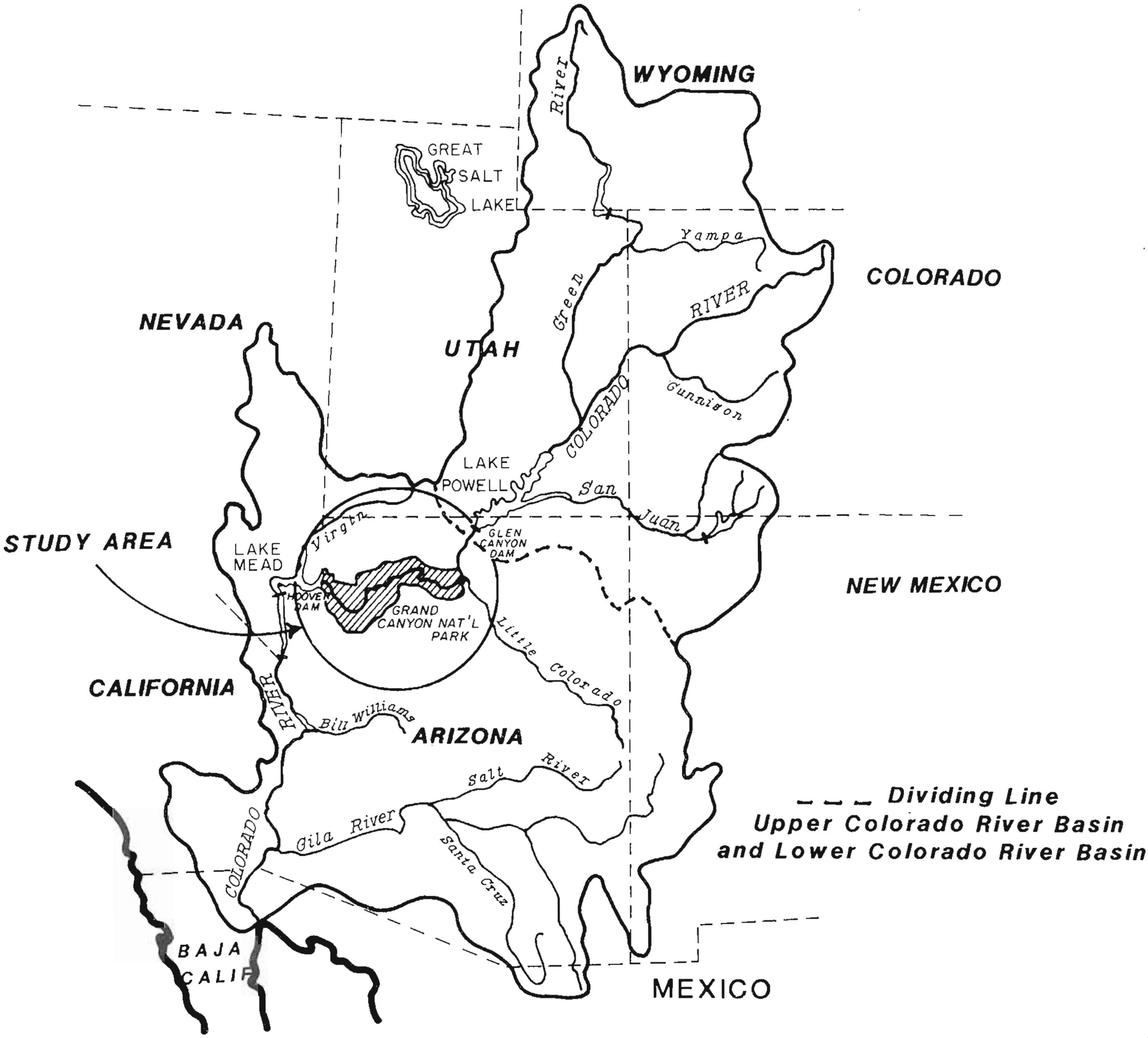

Figure D-1. The Colorado River Basin drains an area of over 244,000 square miles.

The Upper Colorado River Basin drains an area of 108,335 sq mi. Its tributary basins include the Upper Colorado River, the Green River, the Gunnison River, and the San Juan River. The Lower Colorado River Basin drains an area of 135,665 sq mi and includes the Lower Colorado River, the Little Colorado River, the Virgin River, and the Gila River as its tributary basins.

The scarcity and unpredictable availability of water in the areas served by the river have resulted in a need for control and a long history of competition for this resource. Over the past 100 years, the use of the Colorado River has increased at an accelerating rate. Originally the primary beneficiaries of the Colorado River were those who lived along its banks and irrigated from it. Now the use of the river has expanded to urban and industrial areas many miles away.

Today, over 644,000 acres of irrigated land in the Upper Basin and over 1.5 million acres of irrigated land in the Lower Basin are developed. The Colorado River system reservoir storage capacity totals over 61.5 million acre-feet (maf) and can provide over 3,624,000 kilowatts (kW) of electrical capacity. Given the importance of this resource to the area and the magnitude and complexity of the demands upon it, it has been necessary over the years to define use of the river through a number of Congressional acts, court decisions, treaties, and compacts known collectively as the "Law of the River" (Nathanson 1978).

The management of the water resources of the Colorado River is a combined Federal and state process. The Bureau of Reclamation (BOR), through the Upper and Lower Colorado Regional Offices, manages the operation of the dams and reservoirs of the Colorado River. Western Area Power Administration (WAPA) manages the marketing and distribution of the electrical energy that is produced at the dams. The management of the water resources of the Colorado River is the responsibility of the Secretary of the Interior in consultation with the states of the Colorado River Basin. The states' input into the management role is through the Colorado River Management Task Force, which is composed of representatives from each of the Colorado River Basin states.

SECTION II:
WATER MANAGEMENT OF THE COLORADO RIVER BASIN

Management of the Colorado River Basin was recommended by John Wesley Powell (1962/1878) as early as 1878. E.C. LaRue (1916) was among the first of many investigators to suggest that the development of a comprehensive water supply study of the Colorado River was necessary. Growing pressure from the states to determine storage needs and available water supplies led to the 1922 Colorado River Compact (Nathanson 1978).

This compact, an agreement among the Colorado River Basin states (Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming) and the United States, divided the drainage into the Upper and Lower Basins. The dividing point, termed the Compact Point*, was established in the mainstem of the Colorado River one mile below the mouth of the Paria River (Lee Ferry). The Colorado River Compact allocated water to those states from which waters naturally drain into the Colorado River **above** and **below** the Compact Point, apportioning, in perpetuity, 7.5 million acre-feet (maf) annually to each the Upper Basin and the Lower Basin. In addition, the Lower Basin was given the right to increase this apportionment by as much as 1.0 maf in any given year. The most important operating provision in the Colorado River Compact is the required delivery at the Compact Point of 75.0 maf for any period of ten consecutive years. This delivery requirement has been strictly followed up to the present time and is not likely to change in the future.

During the three decades after the Colorado River Compact was forged, the water resource development of the Upper and Lower Basins progressed at very different rates. In an attempt to ensure that the conditions of the Compact (as related to each state's apportionment of water) were met, and to provide for protection of their resources, the Upper Basin states worked to secure their rights. As part of this effort, the Colorado River Storage Project (CRSP) Act (P.L. 84-485) was developed in the early 1950s and passed into law on April 11, 1956 (Nathanson 1978).

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* The gaging stations for the Compact Point are the USGS gaging stations called Colorado River at Lees Ferry, Arizona (09380000) and the Paria River at Lees Ferry, Arizona (09382000).

Colorado River Storage Project

The CRSP Act allows comprehensive development of the water resources of the Upper Colorado River Basin and long-term regulatory storage to occur. The original plan for the CRSP was outlined in a letter from the Department of the Interior to the 83rd Congress (U.S. Department of the Interior 1954). The plan explained the need for the Upper Basin states to develop the means to meet their downstream water commitments to the Lower Basin through the control of their water resources.

Originally, the CRSP plan included ten dams and reservoirs within the Upper Colorado River Basin. Eight of the ten dams were to have river regulation as their main purpose, while the other two would be built primarily for hydroelectric power generation. Under the proposal, each of the ten facilities were to be constructed and operated by the BOR. The combined reservoir capacity from the ten projects would equal 48,555,000 acre-feet (af), of which 37,530,000 af would be active storage (storage that is available for hydroelectric power generation) and 11,025,000 af would be inactive storage. Figure D-2 illustrates active and inactive storage for Lake Powell. Of the original ten proposed dams, six were authorized for construction when the CRSP Act became law. This authorized the Secretary of the Interior to construct, operate, and maintain four storage projects and eleven participating projects for irrigation and other related uses. The four main storage projects were the Curecanti (renamed the Wayne D. Aspinall) Unit (including Blue Mesa, Crystal, and Morrow Point Dams), and the Flaming Gorge, Navajo, and Glen Canyon Dams. The key purposes of the storage projects were:

- To regulate the flow of the Colorado River.
- To store water for beneficial consumptive use.
- To provide for the reclamation of arid and semiarid land.
- To provide control of floods.
- To generate hydroelectric power as an incident of the foregoing purposes.

The six dams, with a total storage capacity of 34 maf, were eventually completed as components of the CRSP (U.S. Department of the Interior 1981). Their individual storage capacities are presented in Table D-1.

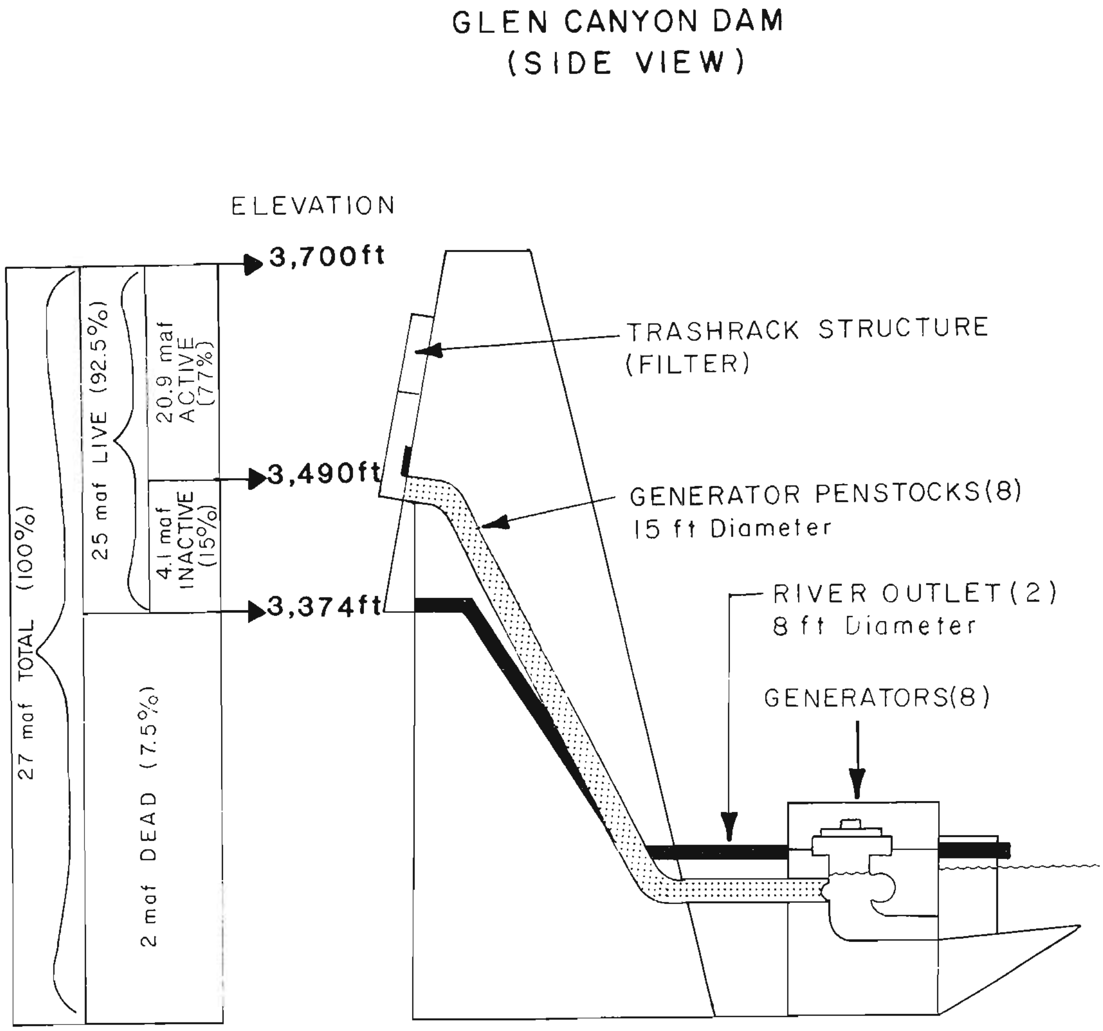


Figure D-2. Seventy-seven percent of the water stored in Lake Powell is available for hydroelectric power generation (active storage).

Table D-1. Colorado River Storage Project reservoir storage.[1]

Unit	Total Capacity[2] (acre-feet)	Live Capacity[3] (acre-feet)	Surface Area (acres)
Glen Canyon	27,000,000	25,002,000	161,390
Flaming Gorge	3,788,700	3,749,000	42,020
Blue Mesa	940,800	829,523	9,180
Morrow Point	117,190	117,025	817
Crystal	25,273	17,573	301
Navajo	1,708,600	1,696,400	15,610
TOTAL	33,580,563	31,411,521	229,318

1 U.S. Department of the Interior 1981
2 Total capacity equals live storage and dead storage.
3 Live capacity equals active storage plus inactive storage.

Glen Canyon Dam was proposed as the highest dam behind which would be the largest reservoir for the mainstem Upper Colorado River. It was to be the key structure in controlling water releases to the Lower Basin.

The hydroelectric powerplants and transmission lines authorized by the CRSP Act were directed to be operated in conjunction with other federal powerplants, present and potential, to produce the greatest practicable amount of power that could be sold at firm power and energy rates. Firm power is the capacity (usually in kW or megawatts [MW]) marketed on a long-term or short-term (usually not less than one month), non-interruptible basis associated with a specific energy rate of delivery. Capacity is the rating (usually in kW or MW) assigned to a generator, station, or transmission system at a maximum load. Energy is the production of electrical generation over time (i.e., work expressed in kilowatthours [kWh], megawatthours [MWh], or gigawatthours [GWh]). Non-firm power is power that is guaranteed to be available continuously and is interruptible upon reasonable notice. The generation of power at the powerplants of the CRSP is incidental to providing conservation of water for domestic or agricultural uses and the controlling of floods. Table D-2 lists the average annual generation at which full load generation is produced and lists the maximum capacity of the CRSP powerplants.

Table D-2. Colorado River Storage Project powerplant capacity.*

Powerplant	Number of Units	Energy (kWh)	Maximum Capacity (kW)
Glen Canyon	8	1,288,000	1,300,000
Flaming Gorge	3	108,000	132,000
Blue Mesa	2	60,000	72,000
Morrow Point	2	120,000	146,000
Crystal	1	28,000	28,000

* U.S. Department of the Interior 1981

Legal criteria of Glen Canyon Dam. The operations of Glen Canyon Dam are controlled by the limiting physical parameters of reservoir size, annual runoff, and discharge capacity, as well as the legal and institutional constraints specified in various federal laws, interstate compacts, international treaties, and Supreme Court decisions. Some of the earliest legislative accords directing the dam **operation** include provisions for the initial filling of Lake Powell as defined in the 1962 General Principles to Govern and Operating Criteria for Glen Canyon Reservoir (Lake Powell) and Lake Mead during the Lake Powell Filling Period **(Filling Criteria)** (Nathanson 1978). Specific dam operating objectives were defined in 1970 (P.L. 90-537) in the Criteria for Coordinated Long-Range Operation of the Colorado River Reservoirs Pursuant to the Colorado River Basin Project Act of September 30, 1968 **(Operating Criteria)** (Nathanson 1978).

Filling Criteria. The Filling Criteria had three main objectives: (1) to provide sufficient water for downstream requirements, (2) to make a fair allowance for any deficiency in energy generation at Hoover Dam due to the impoundment of water behind Glen Canyon Dam, and (3) to bring the storage capacity in Lake Powell to elevation 3,490 feet (ft) at the earliest feasible time. Specific management principles were established to assist in the achievement of these objectives.

Operating Criteria. Section 602 of P.L. 90-537 (Colorado River Basin Project Act) directed the Secretary of the Interior to develop criteria, after consultation with the Colorado River Basin states, consistent with the provisions of the Colorado River Compact, the

Upper Colorado River Basin Compact, and the Mexican Water Treaty. These criteria, called the Operating Criteria, were to cover the coordinated long-range operations of the Upper Basin reservoirs and Lake Mead.

The Act requires the Secretary of the Interior to prepare a report annually that describes the actual operations under the adopted criteria for the preceding year and the projected operations for the current year. The Secretary is to determine if sufficient water exists in storage to meet the downstream deliveries.

The Operating Criteria take into consideration the great diversity among the users and beneficiaries of the Colorado River system and stipulate that any plan of operation must reflect appropriate consideration of the uses of the reservoirs for all purposes, including flood control, river regulation, beneficial consumptive uses, power production, water quality control, recreation, enhancement of fish and wildlife, and other environmental factors. The Secretary of the Interior may modify the Operating Criteria from time to time in accordance with Section 602(b) of P.L. 90-537. The Secretary sponsors a formal review of the Operating Criteria at least every five years, with participation by state representatives and such other parties and agencies as the Secretary may deem appropriate.

The major provisions of the Operating Criteria deal with the release and storage of water in the Upper Basin reservoirs and in the operation of Lake Mead.

<u>Operation of Upper Basin reservoirs.</u> The operation of the Upper Basin reservoirs takes into account the following factors: (1) the objective shall be to maintain a minimum release of water from Lake Powell of 8.23 maf annually, and (2) if the Upper Basin storage reservoirs' active storage forecast for September 30 of the current year is greater than the quantity of storage required by Section 602(a) of the Colorado River Basin Project Act, as determined by the Secretary, and if the active storage forecast for September 30 of the current year of Lake Powell is greater than the Lake Mead active storage forecast for that date, then water shall be released annually from Lake Powell at a rate greater than 8.23 maf to accomplish any or all of the following objectives: (a) reasonably serve beneficial domestic and agricultural needs, (b) maintain, as nearly as practical, active storage in Lake Mead equal to the active storage in Lake Powell, and (c) avoid anticipated spills from Lake Powell.

It should be noted that the Secretary has not made a numerical determination of 602(a) storage. However, each year, the Secretary has determined "that the active storage in Upper Basin reservoirs forecast for September 30, exceeds the 602(a) storage requirement under any reasonable range of assumptions which might be applied. Therefore, the accumulation of 602(a) storage is not the criterion governing the release of water during the current year." It is further noted that the definition of "active storage," pertaining to the Operating Criteria, is considered synonomous with BOR's definition of "live storage," i.e., available storage above the dead storage level.

Operation of Lake Mead. Water released from Lake Powell, plus the tributary inflows between Lake Powell and Lake Mead, shall be regulated in Lake Mead and either pumped from Lake Mead or released to the Colorado River to meet requirements as follows: (a) Mexican Treaty Obligations, (b) reasonable consumptive use requirements of mainstem users in the Lower Basin, (c) net river losses, (d) net reservoir losses, and (e) regulatory wastes.

With the commencement of delivery of mainstream water to the Central Arizona Project in December 1985, the consumptive use requirements of mainstem users in the Lower Basin will be met to the following extent: (a) normal: the annual pumping and release from Lake Mead will be sufficient to satisfy 7.5 maf of annual consumptive use, (b) surplus: the Secretary shall determine from time to time when water in quantities greater than "normal" is available for either pumping or release from Lake Mead, and (c) shortage: the Secretary shall determine from time to time when insufficient mainstream water is available to satisfy annual consumptive use requirements of 7.5 maf.

Historic Operation of Glen Canyon Dam

The closure and water release management of Glen Canyon Dam has had an impact on the flows of the Colorado River through the Grand Canyon. Three distinct phases of river flow can be interpreted from the flow records maintained at Lees Ferry. Figure D-3 illustrates the changes in the pattern of flows at Lees Ferry through these phases.

Phase I. Pre-dam, 1922-1962.
Phase II. Lake Powell filling, 1963-1980.
Phase III. Lake Powell post-filling, 1981-present.

Phase I. Pre-dam, 1922-1962. The pre-dam period was characterized by frequent very high flows in the late spring and early summer seasons and by very low flows during the late summer, fall, and winter seasons. Mean daily flows in excess of 80,000 cubic feet per second (cfs) were not uncommon and were occasionally as high as 100,000 cfs. Flows less than 3,000 cfs were frequent during the fall and winter months. Average daily flows greater than 30,000 cfs occurred about 18 percent of the time, and flows less than 5,000 cfs occurred about 20 percent of the time. Such a range of variation in flows is typical of any major river without significant regulation capabilities.

Phase II. Lake Powell filling, 1963-1980. Lake Powell began storing water in March 1963, and was filled in June of 1980. The management of Lake Powell and the operation of Glen Canyon Dam functioned under the Filling Criteria, whose primary purpose was to ensure efficient filling of Lake Powell while minimizing the impact to the downstream operation of Lake Mead.

Very little water was released through Grand Canyon for the first two years after dam closure (about 2.5 maf each year). In 1964, Lake Powell achieved the minimum elevation necessary for production of power (3,490 feet [ft]). However, the Lake Mead elevation dropped below rated head (elevation 1,123 ft) to a low of 1,088.1 ft in December, prior to spring runoff being available to pass through both reservoirs to meet downstream water use requirements. Subsequently, nearly 11 maf of water was released from Glen Canyon in 1965 to restore the rated head at Lake Mead without lowering Lake Powell below elevation 3,490 ft. As 75 maf is legislated by the Colorado River Compact to be delivered to the Compact Delivery Point (Lees Ferry) in any consecutive ten-year period, annual releases from Glen Canyon Dam were targeted to achieve this goal. Table D-3 presents the flows at Lees Ferry both in annual and cummulative volumes.

As the Operating Criteria was implemented before the termination of the Filling Criteria, the Filling Period was lengthened, accruing additional water deficiencies in Lake Mead. Due to a storage equalization provision, the Operating Criteria caused both reservoirs to gain storage about equally, and Hoover deficiencies were accrued until Lake Powell reached maximum capacity at elevation 3,700 ft (full pool).

COLORADO RIVER AT LEES FERRY

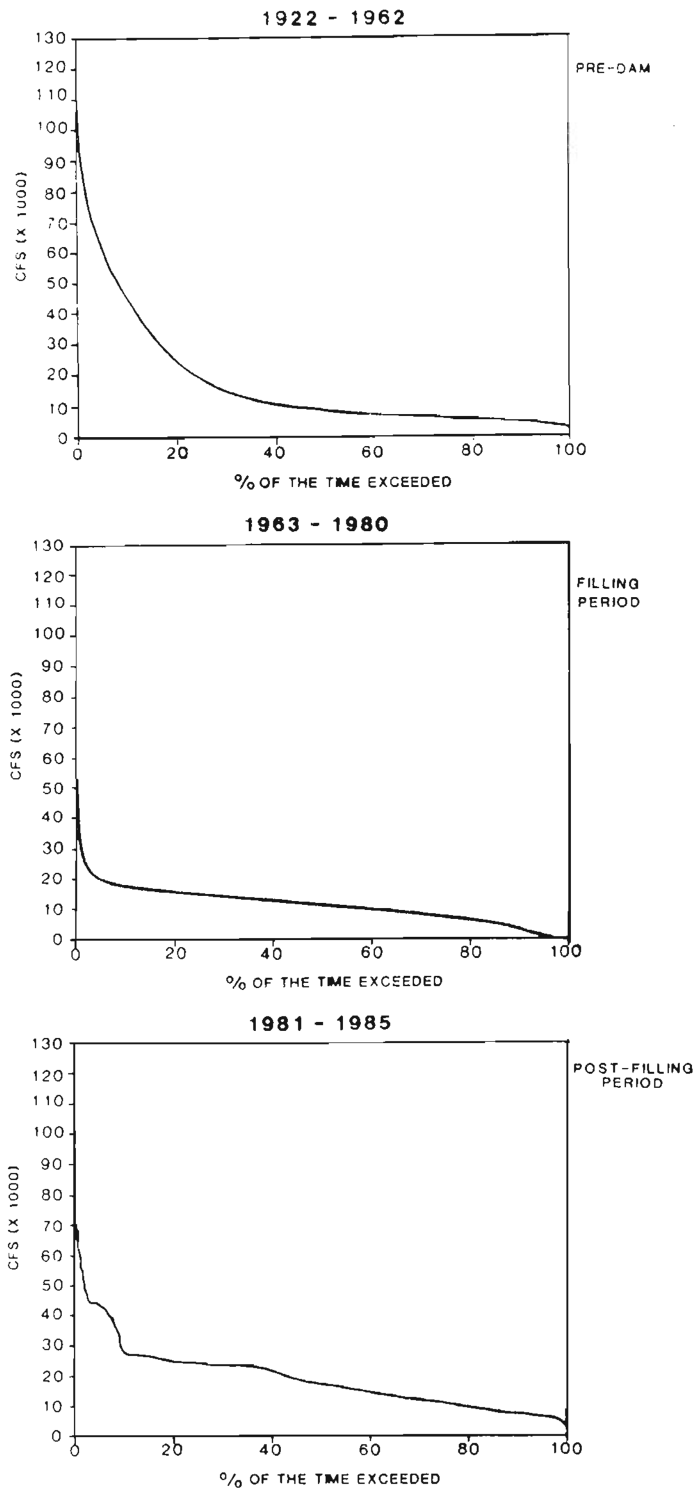


Figure D-3. Flood flows occurred less often during the filling of Lake Powell than during the pre-dam period and the post-filling period (based on monthly flow records).

Table D-3. Filling period of Lake Powell, 1963-1986. Colorado River Flows at Lees Ferry.

Operating Regimes	Water Year	Historic Flow (acre-feet)	Progressive Ten-Year Total (acre-feet)
	1962	14,790,000	99,990,000
	1963	2,520,000	93,705,000
	1964	2,427,000	90,016,000
Filling Criteria (April 1962 to June 1980)	1965	10,835,000	93,544,000
	1966	7,870,000	92,664,000
	1967	7,824,000	83,148,000
	1968	8,358,000	77,246,000
	1969	8,850,000	79,340,000
	1970	8,688,000	78,836,000
	1971	8,607,000	80,769,000
	1972	9,330,000	75,309,000
Operating Criteria (June 1970 to Present)	1973	10,141,000	82,930,000
	1974	8,277,000	88,780,000
	1975	9,274,000	87,219,000
	1976	8,494,000	87,843,000
	1977	8,269,000	88,288,000
	1978	8,369,000	88,299,000
	1979	8,333,000	87,782,000
	1980	10,957,000	90,051,000
	1981	8,316,000	89,760,000
	1982	8,324,000	88,754,000
	1983	17,520,000	96,133,000
	1984	20,518,000	108,374,000
	1985	19,111,000	118,211,000
	1986	16,655,000	126,372,000

The range over which river flows varied during the filling period was smaller than that of the pre-dam period. Flows greater than 65,000 cfs did not exist and flows less than 5,000 cfs occurred only 10 percent of the time.

<u>Phase III. Lake Powell, post-filling, 1981-present.</u> Determining the frequency of various mean daily flows at Lees Ferry during the post-filling period is influenced by the sample size during this period. Only six years of data were available for this analysis. (Eighteen years of data were used for the analysis for the filling period and 41 years of data were used for the pre-dam period.) The post-filling period analysis is also influenced by the preponderance of high flow data. Specifically, 1984 runoff above Glen Canyon Dam was the highest of record and the 1983 runoff was the third highest of record. In addition, 1983-1984 were the highest two consecutive years of record, 1983-1985 were the highest three years of record, and 1983-1986 were the highest four years of record. Since flows in four of the six years in the analysis were unusually high, it is quite likely that the frequency analysis is

biased upwards. Nevertheless, it is useful to note that only 2 percent of the mean daily flows at Lees Ferry were above 42,000 cfs and none were above 85,000 cfs. Even with the data bias, only approximately 10 percent of the flows were greater than 25,000 cfs.

Current Operations

Flows through the Grand Canyon are influenced by storage and release decisions that are made and scheduled annually, monthly, and hourly. The annual decisions are guided by the Operating Criteria. The monthly decisions are generally intermediate targets needed to systematically achieve the annual requirements. The hourly schedules are set to meet the monthly target but are heavily influenced by the power demands and minimum flow requirements. Minimum releases agreed to, but not legally defined, at Glen Canyon Dam are currently 1,000 cfs during the winter and 3,000 cfs during the summer. Other factors are also considered, including emergencies and safety. The following paragraphs discuss the process and procedures used in the determination of annual, monthly, and hourly releases.

<u>Determination of annual release volumes.</u> The release schedules vary greatly in annual release volumes, but each adhere to the Operating Criteria provisions of a minimum release of 8.23 maf and storage equalization between Lake Powell and Lake Mead. Annual releases greater than the minimum are permitted under certain conditions if the reservoir storage in the Upper Basin reservoirs is greater than the storage required by Section 602(a) of the Colorado River Basin Project Act **AND** if the storage in Lake Powell is greater than the storage in Lake Mead. As a practical matter, the reservoir is targeted to fill each July. A general agreement between BOR and the states of Colorado, Utah, and Wyoming established a yearly January 1 target for Lake Powell storage at 22.6 maf as an intermediate target and to achieve full reservoir conditions each July.

Since a full reservoir condition induces the greatest risk of flood releases, it is important to understand the basis for filling the reservoir each year. From a water conservation perspective, a full reservoir pool represents insurance against possible shortages during the drought cycles similar to those that have occurred historically.

Since 1983, releases in excess of 8.23 maf annually have occurred under the Operating Criteria provision of avoiding spills. Excess water is released only to the extent that it is required by the forecast. The impact of this provision has also been to keep Lake Powell full.

Determination of monthly release volumes. The volume of water released from Lake Powell each month depends on the forecasted inflow, the annual storage targets, and annual release requirements described above. Demand for electrical power and energy is also considered and accommodated as long as the release and storage requirements are not affected. The Colorado River Forecasting Service provides the monthly forecasts of expected inflow into Lake Powell. The Forecasting Service uses a satellite telemetered network of more than 100 data collection points within the Upper Colorado River Basin that gather snow water content, precipitation, temperature, and streamflow information. Regression and real-time conceptual computer models use the information to produce forecasted inflows which are then used by BOR to plan future monthly release volumes. Due to the variability in climatic conditions, modeling, and data errors, these forecasts contain large uncertainties. As shown in Figure D-4, the greatest uncertainty occurs in early winter and decreases as the snow accumulation period progresses into the snow melt season, often forcing modifications to the monthly schedule of releases.

If releases are made to avoid anticipated spills, the schedule of the late winter and spring releases has a significant impact on the ability of the reservoir to accommodate unanticipated late spring inflow. Typically, changes in the forecasted inflow have been evenly distributed through the monthly releases remaining in the spring runoff period. This type of operation lowers the risk of not filling the reservoir, but raises the risk of powerplant bypasses. An alternative operation could schedule releases in the January-March period significantly higher than an even distribution would require. Low to moderate flows could be scheduled for the April-June period to compensate for the disproportionately higher earlier releases. In the event that the inflows during this time are larger than expected, releases can be increased without bypassing the powerplant. This type of operation reduces the risk of bypassing the powerplant without substantially increasing the risk of not filling the reservoir. Table D-4 suggests a typical release pattern for three levels of release when the reservoir is expected to fill.

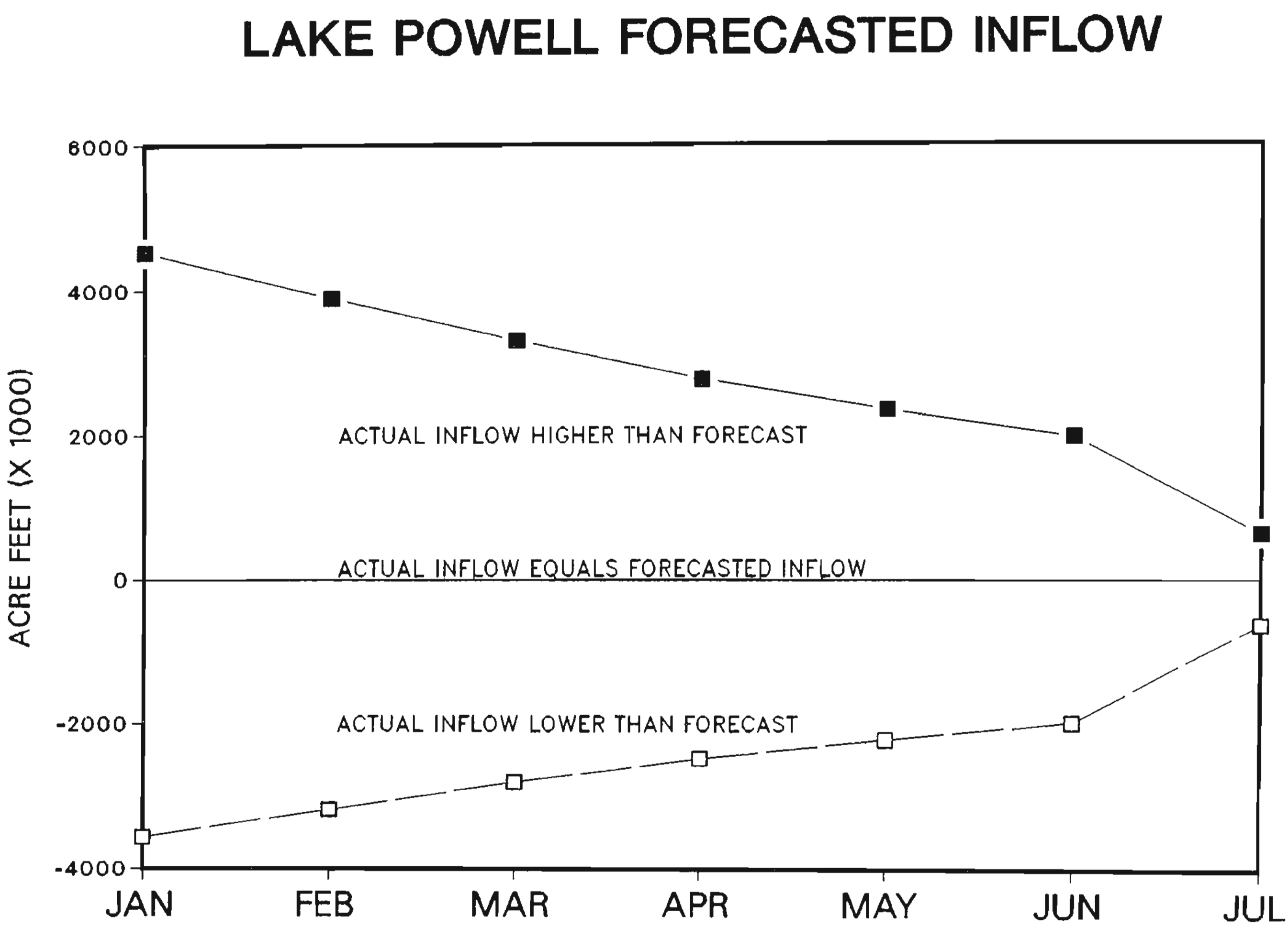


Figure D-4. Lake Powell forecast errors begin with a large potential error which is continually reduced as the runoff season progresses.

Table D-4. Typical water release patterns from Glen Canyon Dam if Lake Powell is expected to fill.

Month	Low Release* 1000af	cfs	Median Release 1000af	cfs	High Release 1000af	cfs
January	1,000	16,263	1,300	24,395	1,500	24,395
February	800	14,405	1,100	25,208	1,400	25,208
March	600	9,758	900	17,890	1,200	17,890
April	550	9,243	880	14,789	1,500	28,569
May	550	8,845	800	14,231	1,500	27,648
June	550	9,243	800	14,285	1,500	28,569
July	1,100	17,890	1,200	26,022	1,600	25,566
August	1,000	16,263	1,300	26,022	1,700	27,648
September	800	13,444	900	23,528	1,300	22,688
October	550	8,945	600	10,571	900	13,824
November	550	9,243	600	10,083	900	16,806
December	950	15,450	1,000	16,263	1,000	16,263
Total	9,000		11,300		16,000	

* Mean monthly cubic feet per second

Very high monthly release volumes severely restrict the flexibility in scheduling. Monthly releases less than 600,000 af do not take advantage of the entire peaking capability and maintain the minimum release rates and conform to the monthly volume. Similarly, monthly release volumes greater than 1,200,000 af require the hourly and daily rates to be near powerplant maximum capacity in order to pass the monthly volume. Naturally, monthly volumes between 600,000 and 1,200,000 af are more desirable from the power production point of view and best meet the mandate to market the maximum amount of power and energy.

If Lake Powell is not scheduled to fill, then a different strategy is used. The minimum schedule of 8.23 maf or the storage equalization provision must apply. Table D-5 identifies potential annual and monthly operations under a non-filling reservoir year. Releases would be patterned for the minimum 8.23 maf or for storage equalization.

Thus, fall and winter releases are designed to meet the January 1 storage target, January through March releases are scheduled to build space in the reservoir to accommodate forecast uncertainty. April, May, and June releases are designed to accommodate the changes

Table D-5. Typical water release patterns from Glen Canyon Dam if Lake Powell is not expected to fill.

Month	8.23 maf Minimum Release 1000af	cfs*	Storage Equalization Release 1000af	cfs
January	900	14,637	900	14,637
February	600	10,804	600	10,804
March	550	8,945	550	8,945
April	550	9,243	550	9,243
May	550	8,945	550	8,945
June	550	9,243	750	12,604
July	1,000	16,263	1,350	21,956
August	1,000	16,263	1,400	22,769
September	630	10,588	1,200	20,167
October	550	8,945	700	11,384
November	550	9,243	650	10,924
December	800	13,011	800	13,011
Total	8,230		10,000	

* Mean monthly cubic feet per second

in inflow as they occur, such that the reservoir is full by July 1. July through September releases are used to compensate for any missed targets and to prepare for the January 1 target of 22.6 maf of storage.

If after all these considerations have been satisfied and monthly releases are flexible, then seasonal variations in the power demand are considered. Power loads are highest during the coldest winter and hottest summer months. Therefore, higher releases are scheduled in these months whenever possible. There is greater flexibility to pattern monthly releases after power loads in years of moderate runoff and reservoir conditions. Figure D-5 illustrates the monthly volumes that show the greatest flexibility in terms of plant operation.

Operational flexibility is greatest when the monthly releases are moderate and least when monthly releases are low or high. When inflows are high, such as occurred from 1983 through 1986, the monthly water releases must be at or near maximum throughout the year and little flexibility exists for managing the water releases for hour-to-hour purposes. Typical operations for 1983 through 1986 involved the powerplant being run at full capacity 24 hours a day.

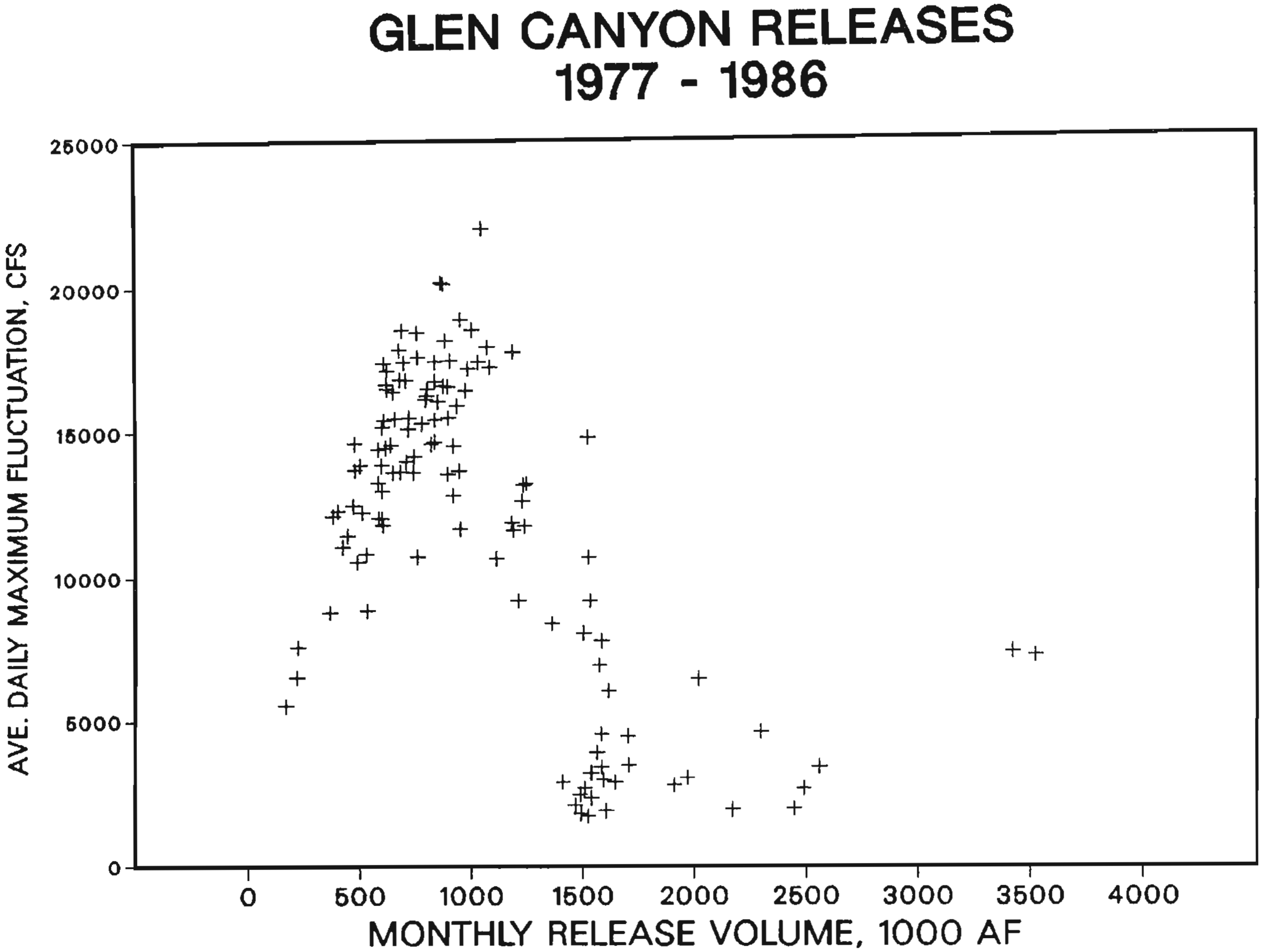


Figure D-5. Monthly release volumes between 600,000 and 1,200,000 acre-feet allow the greatest flexibility in dam operations and result in the maximum amount of release fluctuations.

Determination of hourly release volumes. Hourly releases from Glen Canyon Dam are generally set to reach the monthly release volumes, to maintain established minimum rates, and to follow the pattern of energy demand. The physical limitations of the powerplant provide the boundaries of the managed releases. The maximum turbine capacity is approximately 33,100 cfs, but a limit of 31,500 cfs is presently followed under the direction of the Department of the Interior.

The following guidelines are followed, to the extent possible within higher priority operating constraints, in producing hydroelectric power: (1) bypasses of powerplants are minimized, and to the extent possible, eliminated; (2) water releases are maximized during the peak energy demand periods, generally Monday through Saturday between 7 a.m. and 11 p.m.; (3) water releases are maximized during months of peak energy demand and minimized during low demand months; and (4) sufficient reservoir storage is maintained to assure efficient use of the units.

Demand for power may change the rate at which water is released; however, this demand is never allowed to alter the volume required for other purposes. In a system as complicated as the Colorado River with its associated power transmission system, it is not uncommon for emergency conditions to arise from time to time. These emergencies may cause severe departures from expected schedules. Generally, departures are short-lived and their effect on release volumes can be mitigated rapidly.

Glen Canyon Dam Uprate and Rewind Program. In 1975, an inspection of the generators at Glen Canyon Dam revealed that the original generator windings were reaching their service life and that a rewinding of the generators would be necessary. The rewinding was initiated in 1976. Since this program was classified as a normal maintenance function, no National Environmental Policy Act (NEPA) compliance was necessary.

A decision to uprate the eight generators at Glen Canyon Dam was made to reduce power generation constraints and to provide for an even match of power system components. Because the uprating of the generators was not a normal maintenance function, compliance with NEPA was required. An environmental assessment was completed in December 1982, and resulted in a Finding of No Significant Impact (U.S. Department of the Interior, Bureau of Reclamation 1982). BOR began the uprating of the eight generators at Glen Canyon Dam in 1983. Before uprating, the maximum release was 27,500 cfs at the full-lake level of 3,700 ft, and 31,500 cfs at an elevation at or below 3,641 ft. The elevation of the reservoir determines the head or pressure on the turbines which drive the generators. With reduced reservoir head, greater water releases are required to produce the maximum generator capacity.

The generator uprating process was completed in April 1987. The powerplant can now release a maximum of 32,200 cfs at an elevation of 3,700 ft and 33,100 cfs at an elevation of 3,693 ft. However, an operational cap of 31,500 cfs has been placed on the releases until the completion of the Glen Canyon Environmental Studies. In terms of the present normal operating range of the reservoir (elevation 3,675 to 3,700 ft), the uprated generators have increased the water release capability at full reservoir from about 27,000 cfs to 32,200 cfs. This increases release capability through the powerplant provides an enhanced ability to avoid bypasses and/or spills. This benefit is substantial if releases occur over a length of time. Figure D-6 presents powerplant discharge capability in terms of powerplant generation and reservoir elevation.

To predict future release patterns using the uprated generators, historical hourly release data were analyzed, for **low-medium**, **high**, and **exceptionally high** monthly releases with the following conclusions:

During months with **low to medium** release volumes (400,000 to 900,000 af), the uprated capacity would not be used and there would be no difference in the pre-uprate and post-uprate flow conditions. Months with this release volume have historically had peak releases of 15,000 to 25,000 cfs and were limited by the volume of water available for generation. Off-peak minimum releases during these months were often kept in the 1,000 to 5,000 cfs range in an effort to conserve water for release during the peak power demand portion of the day.

During **high** release months (1,000,000 to 1,500,000 af), historical releases indicate that the percentage of releases greater than 27,000 cfs is at least 10 percent, and the uprated capacity of the generators could be used. If the uprated capacity were used, the extra water needed to increase the releases to 33,100 cfs would be taken from three areas in the daily release

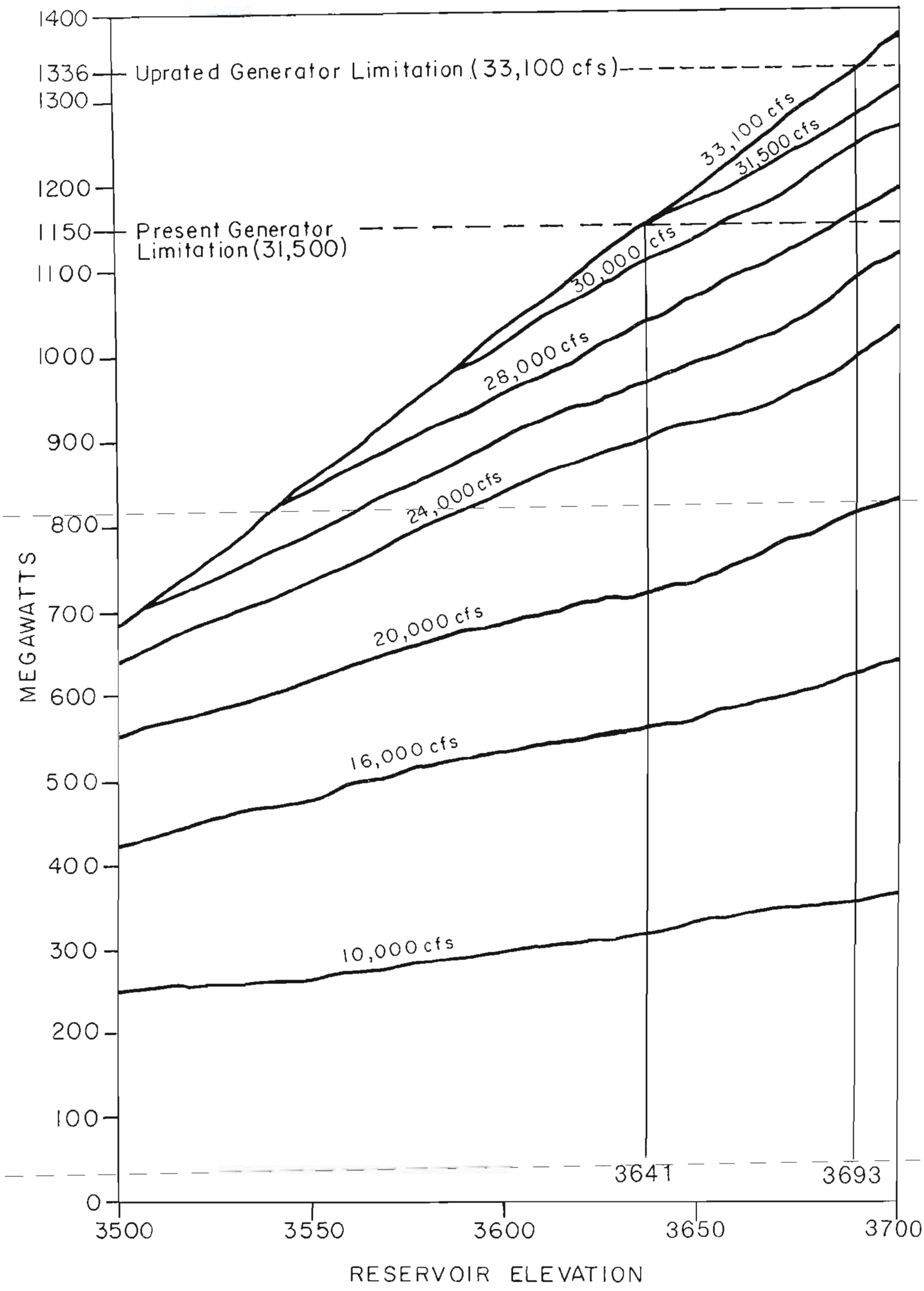


Figure D-6. The two dashed lines represent the present (at 31,500 cfs) and uprated (at 33,100 cfs) generator limits.

hydrograph: release from other peakload hours from the **ascending portion**, peakload hours from the **descending portion**, and from the **minimum daily release** hours.

If water is taken from the **ascending portion**, the daily range of fluctuation would increase but the probability of low flows and the hour-to-hour rate of change of releases would remain as at present. This condition would have minimal impact on the river below the dam.

If water is taken from the **descending portion**, the rate of change of hour-to-hour releases would increase, but the total daily fluctuation and low releases would remain as at present. If water is taken from **minimum daily release** hours, two actions are possible. Either (1) the daily low flows would decrease about 2,000 cfs, the total daily fluctuation would increase, and the hour-to-hour rate of change would remain as at present; or (2) water would be taken from off-peak days (such as weekends or holidays) and moved to on-peak weekdays. However, since the pre-uprate low flows occurred during moderately high months when these volumes were 8,000 to 15,000 cfs, the decreased release due to using the uprates would be well above the currently established minimum flow releases. Marketing and hourly operating strategy of the electrical resource will influence which of these actions will occur in the future.

During **exceptionally high** release months (1,600,000 to 1,900,000 af), the uprated capacity would be used almost constantly due to the need to release as much water as possible through the powerplant. Such monthly releases would occur during extreme runoff years or as the result of large forecast errors. In these instances, the uprates would provide a major benefit by reducing the frequency and magnitude of bypasses later in the runoff season. These releases would essentially be a constant flow of about 33,100 cfs.

SECTION III: RISK OF FLOOD RELEASES

The ideal operating plan would enable the reservoir to fill each year without risking undesirable or damaging flood-level releases. Unfortunately, forecasted inflows have a large degree of uncertainty which amplifies the risks of either flood releases or not filling the reservoir. To evaluate the probability of releases greater than 31,500 cfs, the following assumptions were made: (1) the reservoir storage on January 1 of each year is 22.6 maf, (2) the powerplant release capacity is 31,500 cfs (approximately 1.9 maf/month), (3) the reservoir is assumed to be full by July 31 of each year (27 maf), (4) unanticipated inflow is accommodated by additional releases distributed evenly over the remaining months of the runoff season, and (5) seven generators are available during January through March and eight generators are available for April through July.

Flood releases under these assumptions could occur from two conditions: (1) from an extreme runoff which could not have been contained even with full powerplant discharges starting January 1, or (2) from unanticipated large, late-season changes in the inflow which exceeds the remaining storage and release capability. It is acknowledged that these two conditions are not statistically mutually exclusive. Subjective operating philosophy impacts the ability to accommodate late spring changes in the forecast and causes difficulties in quantifying the probability of flood releases. Probabilities produced by the following methods should be viewed as estimates.

<u>Stochastically Generated Annual Flows.</u> For the purposes of an approximate analysis, it is assumed that the high runoff conditions should be recognized on the first of the month (e.g., January 1, February 1, etc.) and that the reservoir storage on this date would be consistent with the operations. Releases of 31,500 cfs were assumed to begin immediately upon recognition of the high runoff situation. Based on an assumed set of depletions, evaporation, and the historically based natural inflow, the number of spill situations during 1906 through 1984 were counted. The probability values produced varied from 1 in 25 in January to 1 in 3 in June. Therefore, if it were not recognized until late spring, the risk of flood releases would be high.

Analysis Based on Forecast Error. As shown in Figure D-4, the 5 percent and 95 percent confidence bands on the forecasted inflows are wide in January and decrease during the runoff season. An analysis was made of the average, upper decile, and lower decile forecasted inflows, and typical operating levels were established. Probability levels of late spring forecast errors were added to the forecasts to observe the effect on reservoir levels. These additional forecast errors were incorporated in the operating plans for each of the spring runoff months. The probability level of error which produced a flood release was estimated at 1 year in 4.

From the two analyses, an estimated risk of flood releases of 1 year in 4 was adopted for use in this report. Further statistical analysis is planned to evaluate the risk of flood releases. As Upper Basin depletions increase in the future, the probability of the elevation of Lake Powell being significantly drawn down will also increase, even with minimum releases of 8.23 maf. When this situation occurs, the risk of flood releases will drop to near zero until the reservoir refills.

One of the key criteria for the operation of Glen Canyon Dam is to minimize bypasses of the powerplant, i.e., avoid flood releases. Therefore, under high inflow conditions, releases are held at or near 31,500 cfs until it becomes obvious that greater releases will be needed. Due to the acknowledged uncertainties in forecasts, the decision to exceed 31,500 cfs is often delayed in the hope that actual inflow will be less than that forecasted and flood releases will be unnecessary. If the forecast proves to be correct, however, or even underestimates inflow, this delay necessitates releasing larger flows than would have been required had flood releases been started earlier.

SECTION IV:
POWER MARKETING - COLORADO RIVER STORAGE PROJECT

In 1961, BOR initiated the development of a plan to market power from the CRSP. A public participation process assessed the interest in the power and developed long-term firm power contracts for the future energy to be produced by the CRSP powerplants, including the yet to be built Glen Canyon Dam.

The marketing criteria considered the following items: (1) what the source of power would be, (2) how much power would be available and when, (3) who would be eligible to participate and receive the power, (4) how the resource was to be allocated, (5) how the power was to be delivered and where, and (6) the provisions and restrictions contained in the firm power contracts.

On March 9, 1962 (Nathanson 1978), Secretary of Interior Stewart Udall issued the General Power Marketing Criteria which identified the following components necessary for the distribution of the CRSP power:

(1) Market Area: defined the market area in terms of a Northern and Southern Division. Figure D-7 depicts the CRSP Market Area under the 1986 criteria.

(2) Service Seasons: established a six-month winter and summer season.

(3) Basis of Allotments: identified general terms of how the CRSP power would be divided among customers.

(4) Priority and Allotments: established the priority of the applications for preference customers for initial and subsequent allocations of power.

(5) Basis for Firm Power Supply: defined the amount and schedule of power to be available, and other related conditions.

(6) Energy Limitations: established the limit of the United States obligation to deliver energy to project customers (2,550 kWh per kW per season).

COLORADO RIVER STORAGE PROJECT

POWER MARKETING AREA

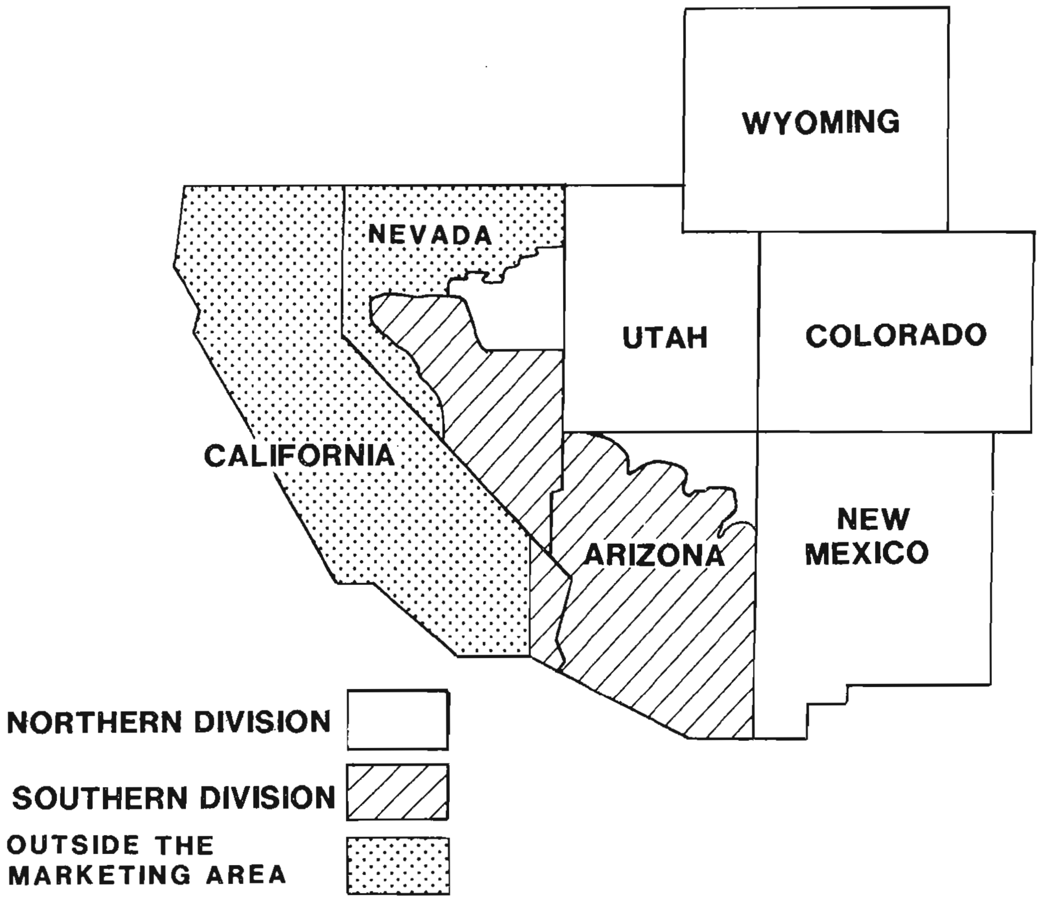


Figure D-7. Western Area Power Administration markets power over a large area of the western United States.

(7) Delivery Conditions: detailed the delivery points and voltages for receipt of CRSP power.

(8) Points of Delivery: defined obligations of the contractor to arrange for additional transmission of CRSP power beyond the established federal points of delivery.

Formation of Western Area Power Administration

On August 4, 1977, the Department of Energy (DOE) was formed (U.S. Congress 1980) and assumed federal power marketing responsibilities. The Western Area Power Administration (WAPA) was established in 1977 as an agency within DOE by Section 302 of P.L. 95-91 to market and transmit federal power in 15 central and western states. WAPA operates and maintains roughly 16,200 circuit-miles of transmission lines and 240 substations, covering a distribution area of 1.25 million sq mi. Power generated by BOR, the Army Corps of Engineers, and the International Boundary and Water Commission is sold through WAPA to 572 municipalities, rural electric cooperatives, public utility districts, private utilities, federal and state agencies, irrigation districts, and other project-use customers. These power sources provide 9,930 MW of installed capacity, capable of generating 45,200 GWh of energy annually.

Modification of the Marketing Criteria

With the creation of WAPA, the original 1962 General Power Marketing Criteria (Figure D-7) for the CRSP hydroelectric power required changes to redefine the geographic market area, the availability of peaking power, and additional delivery points and conditions. Modifications were made through the public participation process and approved on February 9, 1978 (U.S. Department of Energy, Western Area Power Administration 1986). A provision extended the termination date of the original and recent contracts to September 30, 1989, allowing for a more efficient accounting process. In addition, the new marketing criteria provided a new class of service with the availability of long-term firm and peaking power capacity of 1,324 MW in both the winter and summer seasons.

<u>Responsibilities of WAPA and BOR.</u> With the authorization of WAPA, it became necessary to specify the responsibilities of BOR and WAPA. An agreement

signed March 26, 1980, defined the two roles: BOR manages the reservoirs and generates hydroelectric power and WAPA markets and transmits power to the customers.

BOR's responsibilities are to plan, design, construct, operate, and maintain the hydroelectric powerplants authorized by Congress. BOR schedules the release of water from the Upper and Lower Basin powerplants and operates the generating units. They coordinate with WAPA by including WAPA in water release decisions, and to the extent possible, providing WAPA with the opportunity to optimize the utilization of power resources.

WAPA's responsibilities are to plan, design, construct, operate, and maintain the transmission system. They market federal power and set rates to assure that revenues are sufficient to accomplish repayment of all the allocated investment. Other responsibilities of WAPA include controlling the operation and maintenance of high voltage lines, substations, and equipment; administration of safety procedures; operation of principal tie lines and switching; and scheduling of energy transactions with connecting utilities. And finally, they provide power transmission, switching, wheeling arrangements, and substation service for BOR's projects.

WAPA markets the power generated from the CRSP within a six-state area (Figure D-7) ranging from Wyoming to Arizona. The marketing of the federal power is governed by several statutory criteria, including: (1) preference in the sale of power must go to municipalities, public corporations, cooperatives, and nonprofit organizations; (2) revenues generated from the sale of power must be adequate to pay for the total costs of generating the power and all allocated investment costs identified under the original CRSP Act; and (3) the power must be marketed at the lowest possible rates consistent with sound business practices.

Power Marketing by Western Area Power Administration

The power generated at Glen Canyon Dam and the other powerplants of the CRSP system is marketed by WAPA either on a long-term firm basis through electrical sales contracts, or on a short-term basis through agreements with firm power customers or associated utilities interconnected with the CRSP transmission system. The marketing of the power is based on long-term marketing criteria and contracts, short-term marketing of resources, and the process of power investment repayment and financial obligations.

Long-term marketing. The determination of the amounts of power available for long-term marketing and the distribution of this power to utility sytems is a cooperative effort between BOR and WAPA. BOR utilizes the Colorado River Simulation System (CRSS) computer model (U.S. Department of the Interior, Bureau of Reclamation 1985) and the historical hydrological data base to predict available resources for future time periods. The CRSS computer model utilizes anticipated Upper Basin water depletions, historical hydrological conditions, known reservoir storage capacity, and known and anticipated physical resources to predict the availability of power resources. WAPA assesses the availability of the resource, with consideration given to the predicted probability of occurrence of varying levels of resource during future periods. This assessment results in a proposed level of risk associated with a particular level of resource to be offered.

After the completion of the initial resource assessment, WAPA begins the development of a formal marketing plan and development of criteria through the public participation process. The resulting marketing criteria provides the framework for the allocation of the available resources and the preparation of long-term firm power contracts.

With the development of marketing criteria, WAPA requests and accepts applications for power from eligible entities, prepares allocations, and negotiates and executes formal, long-term power contracts with preferred customers. WAPA takes the power generated by BOR and delivers this power to customers at agreed to points of delivery on the interconnected transmission system.

WAPA's customers mostly purchase power from the CRSP system to complement other sources of electrical generation. The large baseload thermal generators, which utilities generally operate continuously at or near maximum output, are the most fuel efficient and hence the most economical to operate. During a normal day of operation, a utility will use a mixture of electrical resources to balance its needs. Typically, a utility will increase generation early in the morning as demand increases. If demand continues to grow, utilities will increase their generation by bringing on line less-efficient interim units. As the demand continues to grow, the utility will subsequently bring on additional units, called peaking units. These are generally oil- or gas-fired, and serve for a relatively short period of time at a substantially higher cost per unit of energy generated. The resources of the CRSP are most commonly used to supplement this need for peaking power and displace the power generated by the less efficient and more costly peaking units. During the nighttime hours, an excess of power is available and the cost for that power is substantially reduced. During nighttime, CRSP powerplants reduce generation in order to save the potential power resources for the peaking period. Figure D-8 shows the ways different kinds of generation are mixed.

The CRSP system is also commonly managed to store off-peak energy from thermal generating sources for use during peakload hours. This is called "shaping" and is accomplished by requiring firm power contractors to take a portion of their energy during off-peak hours. The water that would have been released during the off-peak period is stored in the reservoir and the energy is delivered to the customer from thermal energy sources. During the peakload hours, the water that was stored is released and the power generated is sold to displace the high priced peaking units.

The CRSP system is also used to regulate the generation to match minute-by-minute load changes. A hydro unit's efficiency is relatively high over a large range of use, while a thermal unit's efficiency changes significantly from low load to full load. The CRSP system is also utilized as a "backup" generation capacity in case an unexpected outage or emergency situation occurs.

Short-term marketing. When the available resource is greater than the defined electrical demand, a portion of the resource may be identified to be surplus to that needed to meet firm load commitments. This may be in the form of: (1) surplus energy resulting from generation above firm commitment, (2) excess capacity usually available since long-term capacity will be exceeded 9 out of 10 years, and (3) excess capacity resulting from the mechanical addition or modification to generating units by BOR. WAPA identifies and markets these surpluses on a short-term basis as a component of the overall marketing program.

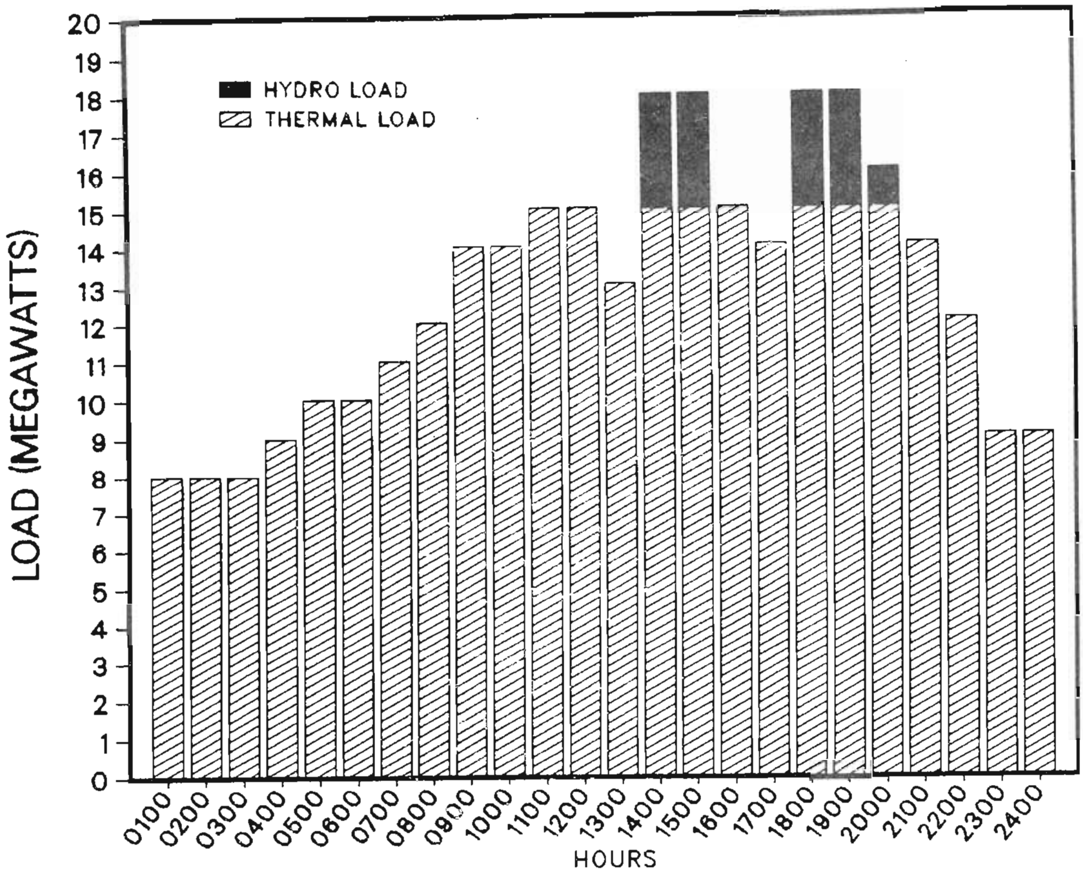


Figure D-8. WAPA`s customers purchase CRSP power to supplement thermal generation. (Note: this is for illustrative purposes only, and is not intended to represent the actual load pattern of any of the CRSP customers.)

Determination of seasonal surpluses. Surplus generation may be available on a month-by-month or a seasonal basis. This surplus is directly related to the runoff forecasts and resulting Glen Canyon Dam release program. In anticipation of high inflow to Lake Powell, BOR may choose to increase monthly release volumes, which translate directly into increased generation available for short-term marketing. The surplus generation may be offered on a monthly or seasonal basis to long-term existing firm power customers. The rate paid for this additional energy is the firm energy rate in place at that time.

When BOR rewound and uprated the generating units at Glen Canyon Powerplant, it became possible to make additional capacity available for short-term marketing. After consideration of anticipated maintenance activities and other operational requirements, WAPA may offer this additional capacity to firm power customers or to others. Since no additional energy is associated with this capacity, the result is a short-term increase in the capacity entitlements to existing customers accepting this additional resource.

Fuel Replacement Program. WAPA also sells Fuel Replacement Energy as an additional short-term marketing activity. In 1972, as part of an in-house conservation program, BOR developed an Oil Conservation Program, later renamed the Fuel Replacement Program. The objective of the Fuel Replacement Program was to conserve fossil fuels in the production of energy by displacing their use with domestic renewable hydropower generation or low-cost, off-peak thermal purchases. Fuel Replacement Energy is nonfirm energy not required to meet firm load and is sold on a short-term basis. Rates are based upon 85 percent of the customer's replacement cost of generation. Since initiation of the program in 1972, it is estimated that BOR and WAPA have displaced the equivalent of 96 million barrels of oil. In 1985, CRSP surplus generation provided approximately 37 percent of the total energy Fuel Replacement sales.

Development of the Post-1989 Marketing Criteria and Long-Term Contracts

Amendments to the 1978 marketing criteria (U.S. Department of Energy, Western Area Power Administration 1986) stated that advance public notice be given prior to changing any marketing criteria. In May 1978, WAPA initiated the public participation process to develop the new marketing and allocation criteria for the post-1989 contract period. On February 7, 1986, WAPA published the "Final Post-1989 General Power Marketing and Allocation Criteria and Call for the Applications for Power" in the Federal Register.

The Post-1989 Criteria made the following changes in the 1978 criteria and 1984 revisions: (1) integrated CRSP with the Rio Grande Project in New Mexico and the Collbran Project in Colorado; (2) increased the marketable resources, with an optional annual purchase of 400 GWh of energy at the customer's request and expense; (3) established a single class of long-term service defined as Long-Term Firm Energy with Capacity; (4) established a 15-year contract term, with provisions for adjustments of the resource commitment after 10 years; and (5) created and allocated a new customer resource pool of approximately 100 MW in either season.

After receipt of applications for power from interested customers, WAPA published the "Final Post-1989 Power Allocations" in the Federal Register on April 2, 1987. Minor allocation corrections were made on May 20, 1987. Allocations were made to 80 eligible customers.

As part of the public participation process for the post-1989 contract period, customers receiving an allocation were given six months, or until September 30, 1987, whichever comes first, to accept the offered electrical service contract. The 1986 criteria requires that all customers must have the ability to receive and distribute power by September 30, 1988, to avoid automatic forfeiture of their contract rights. The 15-year post-1989 contracts are scheduled to begin October 1, 1989, and end on September 30, 2004. Contracts may be revised if additional amounts of energy and capacity are determined to be available by September 30, 1999.

Payback Mechanism - Upper Colorado River Basin Fund

Section 5 of the CRSP Act (Nathanson 1978) established the Upper Colorado River Basin Fund. Revenues collected from the operation of the storage projects and participating projects are credited to this fund. These revenues repay the costs of operation, maintenance, and replacement of all facilities of the CRSP. Section 5 also defined how the revenues would be applied to specific projects. The revenues generated were to provide for (1) the cost of each unit and participating project which is allocated to power, (2) the cost of each unit and participating project which is allocated to municipal water supply, (3) interest of the unamortized balance of the investment in the power and municipal water supply features and, (4) the costs of each storage unit which are allocated to irrigation which is beyond the irrigators ability to repay.

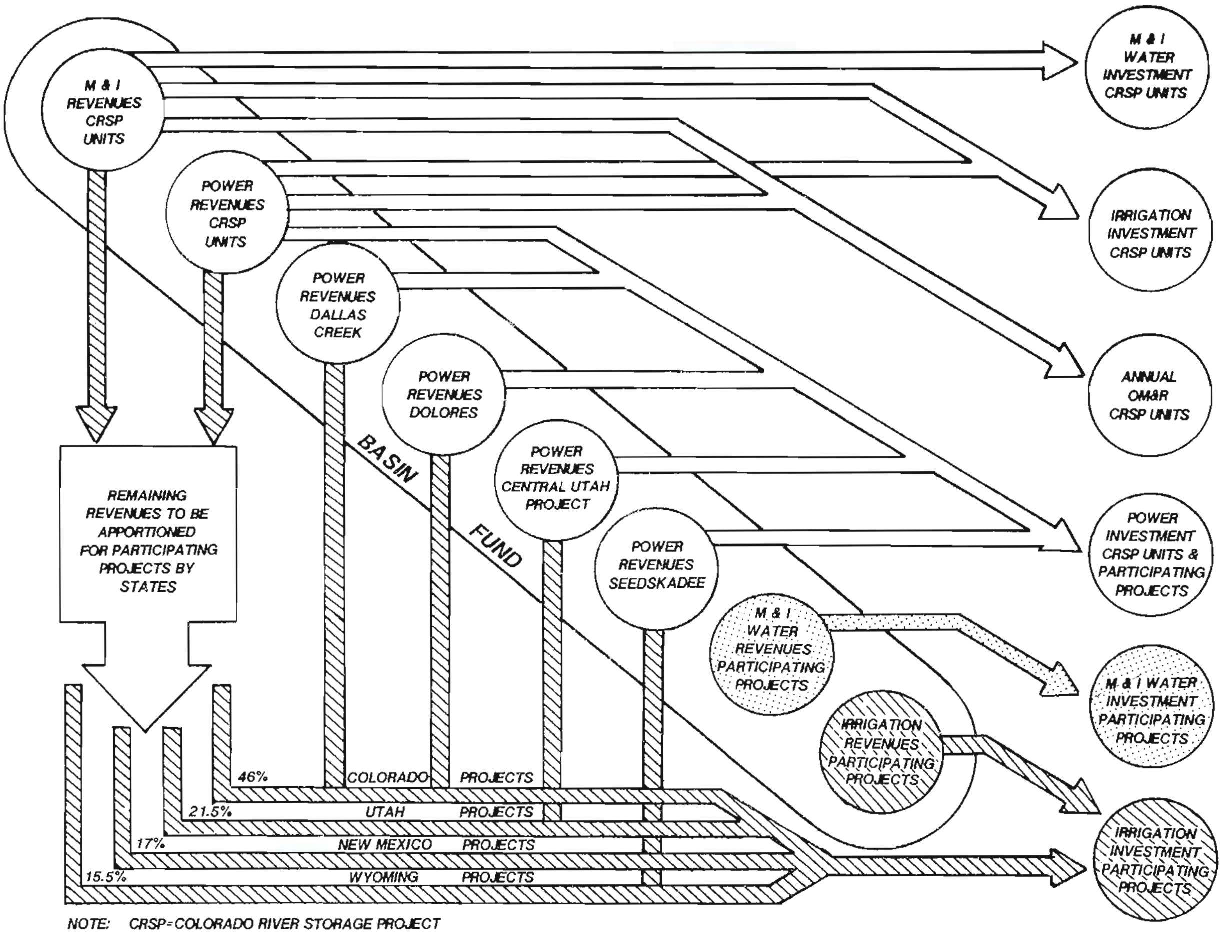
Power repayment studies are prepared annually for each project to determine if rate adjustments are necessary. By law, rates for each project must be set at the lowest level consistent with sound business practices that yields revenues sufficient to repay the federal investment and other costs outlined in the project enabling legislation.

The current CRSP composite firm rate is 9.92 mills/kWh, which reflects a firm capacity rate of $2.09/kW-month and a firm energy rate of 5.00 mills/kWh. A mill equals one-tenth (1/10) of a cent ($.001). This composite rate is the fifth CRSP firm rate adjustment made since the initial CRSP powerplant was completed. The initial composite CRSP firm rate, effective in 1962, was 6.00 mills/kWh. In comparison, the cost of non-renewable fossil-fuel generation can range as high as 60 to 70 mills/kWh.

<u>Source and disposition of CRSP revenues.</u> CRSP revenues come from three primary sources: municipal and industrial water sales, power sales, and irrigation water sales. Figure D-9 shows the manner in which revenues are disbursed from the Upper Colorado River Basin Fund. In addition, revenues from specific state projects may be allocated to repay specific project features and not be generally disbursed.

In Fiscal Year 1986, approximately 55 percent of the total revenue collected from CRSP power-related sales resulted from firm power sales. Fuel Replacement sales accounted for 43 percent of total revenues and transmission, and other services accounted for the remaining 2 percent. From these total revenues, approximately 60 percent went to repay amortization of the federal investment in facility construction. Operation and maintenance costs accounted for 24 percent; 7 percent was used to repay the interest on the federal investment; and an additional 7 percent went to pay for the cost of purchasing power to meet firm power contract obligations. The Fiscal Year 1986 total gross revenues for CRSP amounted to $137,000,000.

UTILIZATION OF THE UPPER COLORADO RIVER BASIN FUND



NOTE: CRSP=COLORADO RIVER STORAGE PROJECT

Figure D-9. The Colorado River Storage Project contributes revenue to the Upper Colorado River Basin Fund. (Upper Colorado Regional Office, BOR, Planning Division, unpublished schematic drawing.)

At the completion of Fiscal Year 1986, approximately 70 percent or $460 million of the $640 million invested in the CRSP power facilities had been repaid. Repayment of power facilities is to be completed by 1995.

Firm power rates. Separate rates are established for each class of service provided by CRSP powerplants. The primary rate is a firm power rate which consists of firm capacity and firm energy components. In the 1977 modifications to the marketing criteria, special rates were established for CRSP peaking capacity. Under the present rate schedule, the peaking capacity rate is the same as the firm capacity rate. In addition, CRSP also provides services for wheeling of firm and non-firm transmission service. A special transmission study is conducted to set rates for these services.

Conservation and Renewable Energy (C&RE) Contract Requirements

In 1980, WAPA initiated its Conservation and Renewable Energy (C&RE) Program. The C&RE program has two major components: (1) an in-house program to improve the efficiency of WAPA's operations and facilities, which includes the initiation of the Fuel Replacement or Oil Conservation Program, and (2) a customer-oriented program, which includes customer assistance, equipment loans, workshops, amd cost-share incentives.

The objective of C&RE is to ensure that federal hydropower is used wisely and to encourage the conservation of energy and the development of renewable resources. A majority of WAPA's customers voluntarily developed C&RE programs. In 1984, the Hoover Powerplant Act (U.S. Department of Energy, Western Area Power Administration 1986) required that all customers have C&RE programs or forfeit up to 10 percent of their contract power.

SECTION V: FUTURE OPERATIONAL CONSTRAINTS

The operational, structural, and climatic constraints that dictate the flow of the Colorado River are very complex and require a sophisticated system capable of responding to political and economic conditions. This system, including the constraints and legal criteria influencing the movement of water through Glen Canyon Dam, will undoubtedly continue to evolve in response to the changing needs for water and electricity in the American Southwest.

Future constraints on the operation of the Colorado River system are exemplified by the following:

(1) The Central Arizona Project will move large quantities of Colorado River water to the interior of Arizona. This action, along with the continued development of the water resources of the Upper Basin states, will decrease the amount of water currently available to the State of California.

(2) The application of the Winters Doctrine, a Federal court ruling, has determined that when Indian reservations were established, water rights were transferred along with the land. Hence, Indian reservations in the Colorado River Basin have a legal right to a certain amount of the waters of the Colorado River. In addition, the National Park Service may have specific water rights also applicable under the Winters Doctrine. As development in the Southwest continues at its rapid pace, water will increase in value, and Indian water rights will eventually become very valuable.

(3) Groups other than Native Americans may also be banking on future dividends from their water rights. Ranchers and farmers are beginning to look at their water rights as their last harvestable crop; rights that can be sold for much more than their land was ever worth.

(4) The potential sale of water rights from the Upper Basin to the Lower Basin is emerging as an important legal and institutional issue. Water has yet to be treated as a commodity which can be bought and sold directly.

(5) Public concerns over the impact of CRSP operations on natural resource values in the Colorado River Basin continue to increase over time. Current studies ongoing in the Upper Basin by the U.S. Fish and Wildlife Service and the BOR are determining the levels of water required for the continued existence of endangered fish species. Habitat requirements for federally-protected fish species may lead to changes in the present operational criteria at other dams in the CRSP.

(6) The evaluation of other legislative directives such as the Grand Canyon Enlargement Act, Endangered Species Act, and other National Park Service legislation should be evaluated.

Management of the Colorado River will always be subject to the influences of politics, economics, law, and science. The complex interrelationships among these four elements combine to form a management system which is not easily understood and even more difficult to modify. Nevertheless, because the operation of the CRSP, particularly Glen Canyon Dam, profoundly impacts the resources of the Colorado River through Grand Canyon National Park, it is imperative that we make the effort to understand and to explore ways that the system might be adjusted to better meet all the demands on the river.

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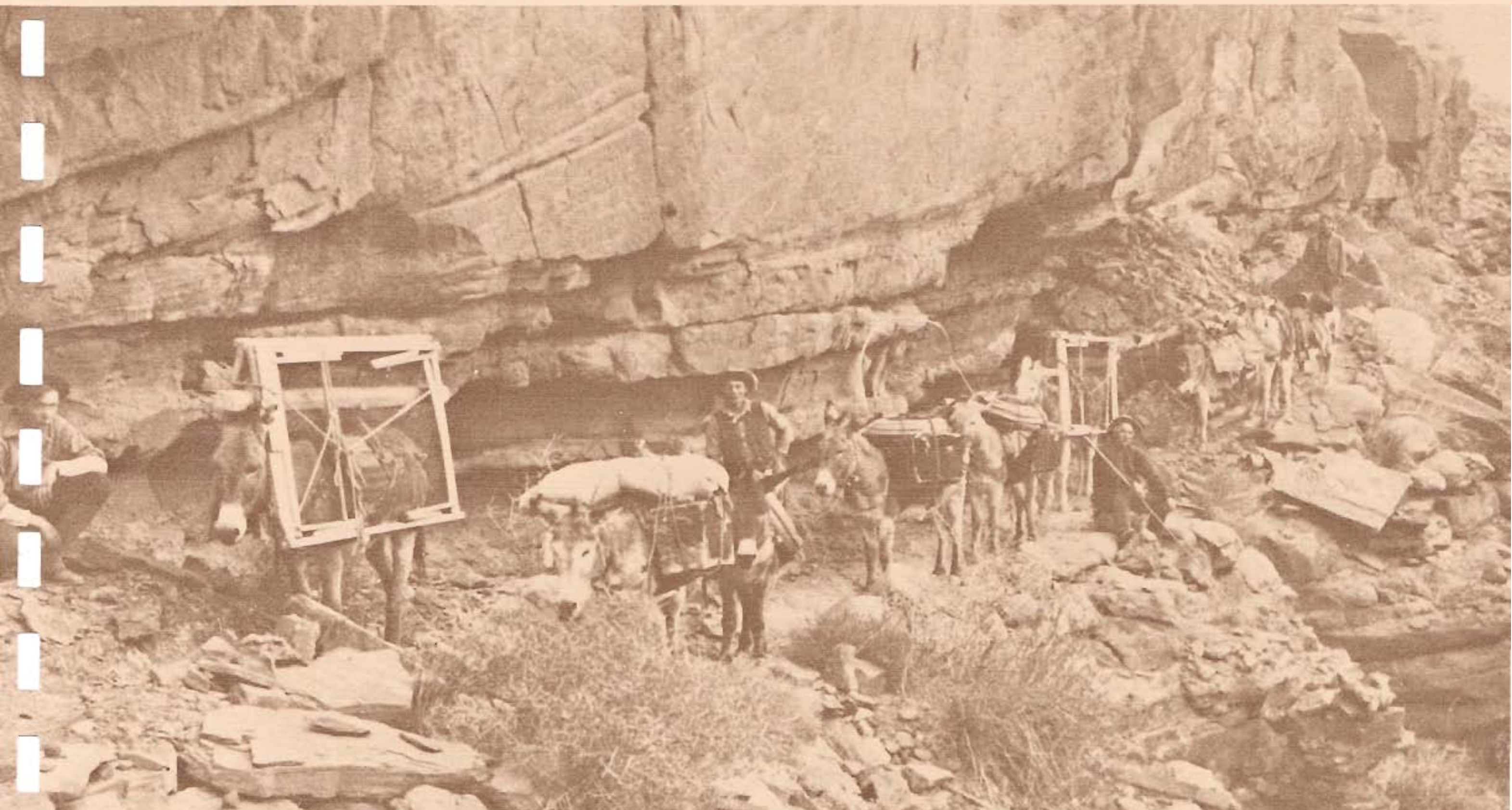

BASS TRAIL
1913
KOLB PHOTO

Below Coconino Formation on the Bass trail about 1913. Photo courtesy of the Emery Kolb collection, Northern Arizona University, Flagstaff, Arizona.

LIST OF INDIVIDUAL GLEN CANYON ENVIRONMENTAL STUDIES TECHNICAL REPORTS

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 27-30), and Dam Operations (Numbers 31-32).

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

Numbers attached to reports in the following list are pending National Technical Information Service numbers.

Three reports (2, 3, and 5) are also available from:

U.S. Geological Survey
Books and Open-File Reports Section
Federal Center, Building 810
P.O. Box 25425
Denver, Colorado 80225.

1. Glen Canyon environmental studies final report.

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)

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) * GET THIS REPORT

4. Sonar patterns of the Colorado River bed in the Grand Canyon. (R.P. Wilson)

5. Recent 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)

6. Sandy beach area survey along the Colorado River in the Grand Canyon National Park. (R. Ferrari)

7. Trends in selected hydraulic variables for the Colorado River at Lees Ferry and near Grand Canyon for the period 1922-1984. (D.E. Burkham)

8. Sediment data collection and analysis for five stations on the Colorado River from Lees Ferry to Diamond Creek. (E.L. Pemberton)

9. Unsteady flow modeling of the releases from Glen Canyon Dam at selected locations in Grand Canyon. (J. Lazenby)

10. Sediment transport and river simulation model. (C.J. Orvis and T.J. Randle)

11. Results and analysis of STARS modeling efforts of the Colorado River in Grand Canyon. (T.J. Randle and E.L. Pemberton)

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)

13. Colorado River water temperature modeling below Glen Canyon Dam. (R. Ferrari)

14. Instream flow microhabitat analysis and trends in the Glen Canyon Dam tailwater. (D.L. Wegner)

15. The effects of steady versus fluctuating flows on aquatic macroinvertebrates in the Colorado River below Glen Canyon Dam. (W.C. Leibfried and D.W. Blinn)

16. <u>Cladophora glomerata</u> 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)

17. Zooplankton of the Colorado River: Glen Canyon Dam to Diamond Creek. (L.R. Haury)

18. Evaluation of riparian vegetation trends in the Grand Canyon using multitemporal remote sensing techniques. (M.J. Pucherelli)

19. Effects of post-dam flooding on riparian substrates, vegetation, and invertebrate populations in the Colorado River corridor in Grand Canyon, Arizona. (L.E. Stevens and G.L. Waring)

20. Aerial photography comparison of the 1983 high low impacts to vegetation at eight Colorado River beaches. (N.J. Brian)

21. The effects of recent flooding on riparian plant establishment in Grand Canyon. (G.L. Waring and L.E. Stevens)

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.S. Anderson and G.A. Ruffner)

23. Fluctuating flows from Glen Canyon Dam and their effect on breeding birds of the Colorado River. (B.T. Brown and R.R. Johnson)

24. Monitoring bird population densities along the Colorado River in Grand Canyon. (B.T. Brown)

25. Monitoring bird population densities along the Colorado River in Grand Canyon: 1987 breeding season. (B.T. Brown)

26. Lizards along the Colorado River in Grand Canyon National Park: possible effects of fluctuating river flows. (P.L. Warren and C.R. Schwalbe)

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)

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) * GET THIS REPORT

29. Boating accidents at Lees Ferry: a boater survey and analysis of accident reports. (L. Belli and R. Pilk)

30. Simulating the effects of dam releases on Grand Canyon river trips. (A.H. Underhill and R.E. Borkan)

31. Colorado River Storage Project constraints and operation of Glen Canyon Dam. (D.L. Wegner)

32. Colorado River law. (D.L. Wegner)

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GLOSSARY

CONFLUENCE
OF
SAN JUAN
1920
EMERY KOLB PHOTO

U.S. Geological Survey team near the confluence of the San Juan and Colorado Rivers, ca. 1920s. Photo courtesy of the Emery Kolb Collection, Northern Arizona University, Flagstaff, Arizona.

GLOSSARY

acre-foot (af): a unit of volume; the volume of water that would cover an acre of land to a depth of one foot; 326,000 gallons or 43,560 cubic feet

active storage: the reservoir capacity that can be used for power generation; at Glen Canyon Dam this is the reservoir storage above the penstock openings at elevation 3,490 feet

af: acre-foot

AGF: Arizona Department of Game & Fish

aggradation: the geologic process wherein streambeds and floodplains and the bottom of water bodies are raised in elevation by the addition of material; the opposite of degradation

algae: simple plants containing chlorophyll; most live submerged in water

alluvial: relating to material deposited by running water, such as clay, silt, sand, and gravel

appropriation: an amount of water set apart or assigned to a particular purpose or use

aquatic: living or growing in water; not terrestrial

attenuation: a reduction of the amplitude of flow fluctuation

attribute survey: survey to determine the important components of the recreational experience

automatic power generation control: the regulation of the power output of electric generators within a prescribed area in response to changes in transmission system operational characteristics

average year: in this report, a release from Glen Canyon Dam equal to 11.3 million acre feet per water year

avian: of or having to do with birds

backwater: a small, generally shallow body of water with little or no current which is attached to the main channel

baseload: the minimum amount of electric power used in a stated period of time

baseload plant: a powerplant normally operated to carry baseload; consequently, it operates essentially at a constant load

baseloading: running water through a powerplant at a roughly steady rate, thereby producing power at a steady rate

bed load: sediment moving on or near the stream bed and frequently in contact with it

bed material: the unconsolidated material of which a streambed is composed

bedrock: the solid rock at the surface or underlying other surface materials

beneficial consumptive use: water loss through use for the betterment of society, i.e. irrigation, drinking, or other municipal use

benthic: of or pertaining to aquatic organisms which inhabit the bottom substrates of streams or lakes

biological opinion: document which states the opinion of the U.S. Fish and Wildlife Service as to whether a Federal action is likely to jeopardize the continued existence of a threatened or endangered species or result in the destruction or adverse modification of critical habitat

blockloading: providing a consistent amount of electrical power in a stated period of time

BOR: U.S. Department of the Interior, Bureau of Reclamation

camping beach: area at the water's edge composed of sand and high enough in elevation to avoid inundation at most flow levels

capacity: The load for which a generator is rated

cfs: cubic foot per second

channel margin deposits: narrow sand deposits which continuously or discontinuously line the channel banks

circuit mile: the geographic or pole miles for power transmission lines

class of service: type of power (firm or non-firm energy) sold to customers

commercial river trip: trips organized by boating companies that conduct tours for paying passengers or customers

community: all members of a specified group of species present in a specific area at a specific time

Compact Point: the dividing line between the Upper and Lower Colorado River Basins--Lees Ferry, Arizona

consumer surplus: the value of a recreation opportunity, above the cost to the consumer; synonymous with recreation benefit; measured using willingness to pay, as specified in Federal guidelines for water resources planning

contingent valuation: survey method asking for the maximum values that recreationists would pay for access to a particular activity

contract date of delivery: that date specified in the firm power contract

control area: part of a power system, or a combination of systems, to which a common electrical generation allocation scheme is applied

CRSP: Colorado River Storage Project

cross-sectional area: the area of a stream, channel, or waterway, usually taken perpendicular to the stream centerline

cubic foot per second (cfs): a unit of discharge, or volume rate of flow; equal to 0.0283 cubic meters per second

dead storage: the reservoir capacity from which stored water cannot be evacuated by gravity; at Glen Canyon Dam this is the reservoir storage below the river outlet works openings at elevation 3,374 feet

debris fan: a sloping mass of boulders, sand, silt and clay formed at the mouth of a stream valley

debris flow: a moving mass of rocks, sand, and clay containing less than 40 percent water by volume

degradation: the geologic process wherein streambeds and floodplains are lowered in elevation by the removal of material; the opposite of aggradation

depletion: the total loss of water from a stream resulting from consumptive uses, evaporation, seepage, and evapotranspiration

diatom: microscopic, single-celled or colonial algae having cell walls of silica

discharge: volume of water that passes a given point within a given period of time; expressed in this report as cubic feet per second

DOE: U.S. Department of Energy

dory: a flat bottomed boat with high flaring sides, sharp bow, and deep V-shaped transom usually made of wood and carrying up to six people total

drawdown: lowering of a reservoir's water level; process of depleting reservoir water storage

drift: movement and dislodgment of aquatic food organisms in the current of a river

ecosystem: a complex system composed of a community of fauna and flora taking into account the chemical and physical environment with which the system is interrelated

eddy: current of water moving against the main current and with a circular motion

energy: the electrical work produced from a power generating unit over a period of time; expressed in kilowatthours

endangered species: any species or subspecies whose survival has been determined to be threatened by extinction according to P.L. 93-205

erode: to wear away or remove the land surface by wind, water, or other agents

excess capacity: power generation capacity available on a short-term basis in excess of the firm energy on a long-term contract offered to an electricity customer

exotic species: introduced species, not indigenous to a given area

extirpated species: a species which is no longer present due to extinction in a given area

F: Fahrenheit, a unit of temperature

fauna: all animal life associated with a given habitat, country, area, or period

firm energy or power: non-interruptible power which is guaranteed by the supplier to be available at all times except for reasons of certain uncontrollable forces or continuity of service provisions

flood: a general and temporary condition of partial or complete inundation of normally dry land areas from the overflow of water; defined here as any release from Glen Canyon Dam in excess of powerplant capacity. During the GCES maximum powerplant capacity was 31,500 cfs

flood control capacity: the reservoir capacity assigned to the sole purpose of regulating inflows to reduce flood damage downstream

fluctuating flows: water released from Glen Canyon Dam that varies in volume with time, within the range of 1,000 to 31,500 cfs, on a daily basis. For purposes of the GCES, flows are defined as fluctuating if they change by more than 10,000 cfs in a 24-hour period.

fossorial insects: insects that live in the soil

fry: life stage of fish between the egg and fingerling stages

ft: feet

fuel replacement energy: electric energy generated at a hydroelectric plant as a substitute for energy which would otherwise have been generated by a thermal electric plant

full pool: the volume of water in a reservoir at maximum design elevation. At Lake Powell this is at elevation 3,700 feet. Total volume is 27,000,000 acre-feet

FWS: U.S. Department of the Interior, Fish and Wildlife Service

gage: a specific location on a stream where systematic observations of hydrologic data are obtained

GCES: Glen Canyon Environmental Studies

gigawatt (GW): a unit of power equal to one billion watts

gradient: the slope or rate of change in vertical elevation per unit of horizontal distance of water surface of a flowing stream

GW: gigawatt

head: refers to power head, the lake depth that will allow the utilization of generators due to the pressure exerted by that column of water

herpetofauna: general grouping for reptiles and amphibians

hydroelectric: of or relating to production of electricity by water power

hydrology: the science dealing with water and snow, including their properties and distribution

hyperconcentrated flow: a moving mixture of sediment and water between 40 and 80 percent water by volume

inactive storage: the reservoir capacity that can be released from the dam but is not available for power generation; at Glen Canyon Dam this is the reservoir storage above the river outlet works openings at elevation 3,374 feet and below the penstock openings at elevation 3,490 feet

index: census of some object or variable related to the true number of animals

indicator species: an organism, species, or community which indicates the presence of an environmental condition or conditions

inflow: water flowing in; in this report refers to water coming into Lake Powell from upstream watersheds

interconnected systems: a system consisting of two or more individual power systems normally operating with connecting tie lines

inundate: to cover with impounded waters or floodwaters

invertebrates: all animals without a vertebral column

iterative process: a process with many repetitions of the same action

juvenile: young of a species

kilowatthour (kWh): a unit of work or energy equal to that expanded by one kilowatt (equal to 1000 watts) in one hour; for example, a 10 kilowatt generator, if operated continuously for one hour will produce 10 kilowatthours of electrical energy

kWh: kilowatthour

Law of the River: group of legislative and international decisions which governs the management of the Colorado River

LCR: Little Colorado River

live storage: the reservoir capacity that can be released through the dam; at Glen Canyon Dam this is the reservoir storage above the river outlet works openings at elevation!3,374 feet; sum of active and inactive storage

long-term regulatory storage: live storage

Lower Basin: three states (Arizona, Nevada, and California) within the Colorado River watershed below Lees Ferry, Arizona

Lower Division: Lower Basin and the area outside the Colorado River watershed to which water may be diverted from the Lower Basin; includes the states of Arizona, Nevada, and California; defined by Article II of the Colorado River Compact

maf: million acre-feet

main channel pool: a reach of river with a low bed elevation, relative to rapids or riffles

mainstem: the main course of a stream

megawatt (MW): one million watts of electrical power

mi: mile

million acre-feet (maf): a unit of volume, the volume of water that would cover one million acres at a depth of one foot

mitigate: to render or become mild or milder, to modify; moderate, or make or become less severe

monomictic lakes: warm-water lakes which turn over once per year (winter) and where the temperature never falls below 4 degrees C

motor boat: a 22- to 37-foot long inflatable raft carrying between 8-20 people total and powered by a motor

mt: million tons

mtd: million tons per day

mty: million tons per year

MW: megawatt

nameplate: the power generation capacity of a generator that can be guaranteed under continuous operation

NEPA: National Environmental Policy Act

New High Water Zone (NHWZ): the area located next to the river colonized with vegetation since the construction of Glen Canyon Dam in 1963 and typically composed of riparian species, both native and exotic

non-firm energy: power that is not available continuously and may be interruptible; may be marketed on a short-term basis

normal year: see average year

NPS: U.S. Department of the Interior, National Park Service

nutrient: any organic or inorganic compound used to sustain life

oar boat: a 14- to 18-foot oar-powered inflatable raft carrying up to six people

obligate riparian species: a species completely dependent upon habitat along a body of water

off-peak demand: power requirement during the period of time (usually between midnight and 7:00 am) when need for energy is low, or seasonally during the spring and fall months when need is generally less than during winter and summer months

Old High Water Zone (OHWZ): an area of vegetation above the level corresponding to flood flows of about 125,000 cfs and typically composed of native leguminous tree species

on-peak demand: power requirement during period of time (usually between noon and 7:00 pm) when need for energy is high, or seasonally during the winter and summer months when need is generally higher than during spring and fall months

operational losses: losses of water resulting from evaporation and seepage

outflow: water flowing out; in this report refers to water leaving Lake Powell by way of Glen Canyon Dam

overamping: exceeding the rated capacity of a system; synonymous with the GCES study manager

peak demand: the greatest power requirement occurring within a specified period

peaking capacity: that additional power generating capacity available at times of peak demand

peaking power: that power which is generated during periods of peak demand

penstock: a conduit or pipe for conducting water, carries water from the reservoir to the powerplant generators

phytophagus insect: plant eating or herbivorous insects

plankton: plants (phytoplankton) and animals (zooplankton) with limited powers of locomotion usually living free in the water away from substrates

plot: an area of land that is studied or used for an experimental purpose, in which sample areas are often located

population: the total of individuals occupying an area; a group of interbreeding organisms that represent the level of organization at which speciation occurs

population density: the number per unit area of individuals of any given species at a given time

post-dam: term used in this report referring to the period of time after Glen Canyon Dam was completed in 1963

power demand: the rate at which electric energy is required and delivered to or by a system over any designated period of time

powerplant: a facility which produces energy for power

pre-dam: term used in this report referring to the period of time before completion of Glen Canyon Dam in 1963

quadrat: a sampling area, most commonly one square meter, used for analyzing vegetation

rated head: the pressure of the reservoir water under which a generator can be operated; it is a function of the depth of the water and the distance that it falls before it drives the turbine

reach: any specified length of stream or conveyance channel

reattachment deposit: a sand deposit located where downstream flow meets the channel bank at the downstream end of a recirculating zone

recirculation zone: an area of flow composed of one or more eddies immediately below a constriction in the channel

recreation benefit: the value of recreational activity to the recreationist, usually measured in dollar terms, above the cost of participating in the recreational activity, which includes expenses for travel, entrance fees and the like; for valuing recreational resources produced through Federal projects, synonymous with the consumer surplus associated with the recreational activity

redd: depression in river or lake bed dug by fish for the deposition of eggs

relict: a group of organisms or a habitat persisting in an environment which has changed from that which is typical for it

remote sensing: methods for determining the characteristics of an object, organism, or community from afar

reservoir: an artificially impounded body of water

resilience: the ability of any system to resist or to recover from stress

revetment: materials or a structure placed to restrain material from being transported away

rewind: act of putting new copper insulated wire in the armature windings of a generator

riparian: living on or adjacent to a water supply such as a riverbank, lake, or pond

risk index: a numeric scale reflecting the hazard associated with white-water boating and fishing from boats in the study area at different river flow levels. The scale combines the risk of various kinds of accidents and equipment damage. Higher values on the scale indicate higher risk, and a zero indicates no risk of accidents.

river mile: a unit of measurement (in miles) used on the Colorado River with River Mile 0 located at the U.S. Geological Survey Gage at Lees Ferry; miles downstream from that point are positive and miles upstream are negative

river outlet works: four 96-inch steel tubes with a combined capactiy of 17,000 cfs that are used to release water through Glen Canyon Dam without using the powerplant

riverine: area comprising the river and riparian corridor

sample error: random variation reflecting the inherent variability within a population being censused

sandbar: a ridge of sand built up by currents, especially in a river

scheduled outage: the shutdown of a generating unit, or other facility, for inspection or maintenance, in accordance with an advance schedule

sediment: unconsolidated material mostly derived from rocks or biological material that is or has been transported by water or wind

sediment discharge: the rate at which sediment passes a stream cross section in a given period of time, expressed in millions of tons per day (mtd)

sediment load: the mass of sediment passing through a stream cross section in a given period of time, expressed in millions of tons (mt)

separation deposit: a sand deposit located at the upstream end of a recirculation zone, where downstream flow becomes separated from the channel bank

spawn: to lay eggs; especially of fish

species: the basic category of biological classification intended to designate a single kind of animal or plant

spill: water exiting Glen Canyon Dam without going through the powerplant generators; in this report, synonymous with "flood release"

spillway: overflow channel of a dam

stage: see water surface elevation

steady flow: flow at any volume which does not vary by more than 10,000 cfs over a 24-hour period

stochastic: statistical analysis involving a random variable, probability, or chance

stream power: the product of the specific weight of water, discharge, and slope of a stream; expressed in pounds per foot-second

succession: a directional, orderly process of community change in which the community modifies the physical environment to eventually establish an ecosystem which is as stable as possible at the site in question

supercritical flow: water whose velocity exceeds the velocity of propogation of a long surface wave in still water

surplus energy: energy surplus to contracted firm load which may be available for a short-term period to serve additional load, usually attributed directly to favorable but unanticipated hydrologic conditions

surplus value: see consumer surplus

surplus water release: in the context of this report, water released from Glen Canyon Dam in excess of 31,000 cfs; synonymous with flood release

tailwater: water below a dam

talus: fragments of rock derived from and lying at the foot of cliffs or steep slopes

terrestrial: not aquatic; refers to the land

thalweg: deepest part of a river channel in a cross section of a river profile

tie lines: transmission line connecting two or more power systems

topography: the physical shape of the ground surface

transect: a line (or belt) through a community on which are noted the important characteristics of the individuals of the species observed

trophic: refers to nutrition

trophic level: place of an animal in the food chain

turbidity: a measure of the extent to which light passing through water is reduced due to suspended materials

Upper Basin: four states (Utah, Colorado, Wyoming, and New Mexico) within the Colorado River watershed above the Compact Point

Upper Colorado River Commission: a commission established by the Upper Colorado River Basin Compact of five appointed members from the Upper Division states (Colorado, New Mexico, Utah, Wyoming) whose purpose is to secure the storage of water for beneficial consumptive use in the Upper Basin

Upper Division: the Upper Basin and the area outside the Colorado River watershed to which water may be diverted from the Upper Basin; includes the states of Colorado, New Mexico, Utah, and Wyoming; defined by Article II of the Colorado River Compact

uprate: modification or replacement of generator equipment that would enable operation beyond present capacity, included in the act of rewinding; involves replacing field windings, strengthening rotor arms, and making mechanical modifications

user-day: one passenger on the river for a day; a unit of measure for recreation use

USGS: U.S. Department of the Interior, Geological Survey

velocity: the speed of water moving down a system; expressed in feet per second

WAPA: U.S. Department of Energy, Western Area Power Administration

water surface elevation (stage): the elevation of a water surface above or below an established reference

water year (WY): period of time beginning October 1 of one year and ending September 30 of the following year and designated by the calendar year in which it ends

wheeling: the use of the transmission facilities of one system to transmit power of and for another system

white-water: frothy water as in breakers, rapids, or water falls

willingness to pay: an approach to estimating the value of recreational activities (and other goods), where value is defined as the maximum amount a consumer would be willing to pay for the opportunity rather than do without. The total willingness to pay, minus the user's costs of participating in the activity, defines the consumer surplus and recreation benefits

WW: white-water boaters

WY: water year

<: a symbol indicating that the value of the quantity to the left of the symbol is less than the value of the quantity to the right of the symbol

>: a symbol indicating that the value of the quantity to the left of the symbol is greater than the value of the quantity to the right of the symbol