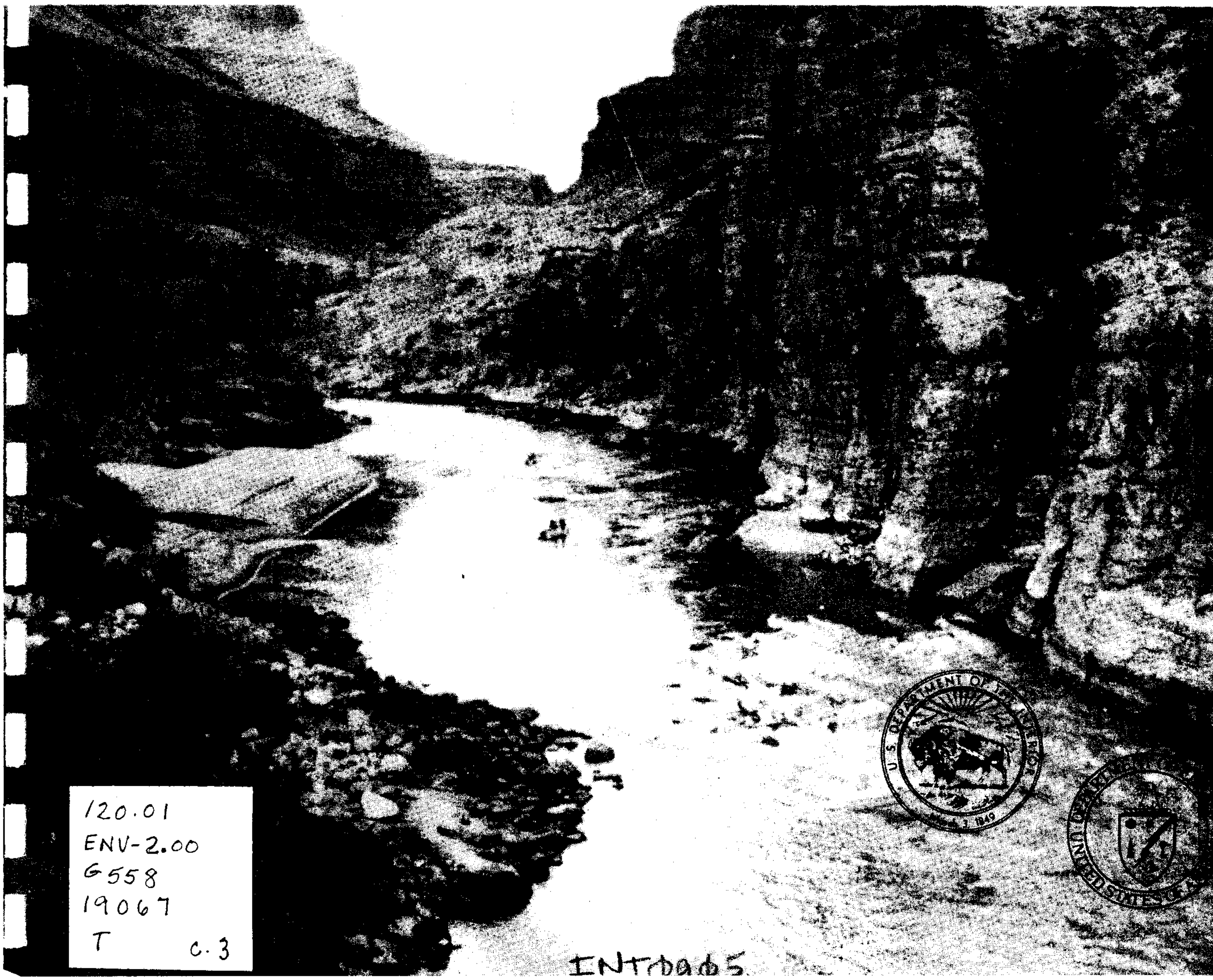
GLEN CANYON ENVIRONMENTAL STUDIES

EXECUTIVE SUMMARIES OF TECHNICAL REPORTS

OCTOBER 1988



GLEN CANYON ENVIRONMENTAL STUDIES

EXECUTIVE SUMMARIES OF

TECHNICAL REPORTS

NOVEMBER 1988

This volume contains executive summaries of the Glen Canyon Environmental Studies Technical Reports prepared by individuals representing the following:

U.S. Department of the Interior
Bureau of Reclamation
Geological Survey
National Park Service

U.S. Department of Energy
Western Area Power Administration

Arizona Game and Fish Department

Private Consultants

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GLEN CANYON ENVIRONMENTAL STUDIES
EXECUTIVE SUMMARY OF TECHNICAL REPORTS

SECTION I: INTRODUCTION

A. The Glen Canyon Environmental Studies

This volume presents executive summaries of 31 of the 33 Glen Canyon Environmental Studies (GCES) technical reports. These reports have been prepared by researchers from government agencies, universities, and private consulting firms which participated in the four-year GCES effort. This volume is a companion to the GCES Final Report.

The 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 portion of river flows first through 15 miles of Glen Canyon National Recreation Area, then through 277 miles of the Grand Canyon National Park upstream of Lake Mead.

B. Objectives of the Glen Canyon Environmental Studies

In recognition of the concerns of the public and government agencies, the Bureau of Reclamation was directed by the Secretary 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, low, and high flows to determine the effect of those flows on resources.

The GCES effort was a cooperative effort among the Bureau of Reclamation, the National Park Service, and the U.S. Fish and Wildlife Service. Cooperation and contributions to the study came from the Arizona Game and Fish Department, the U.S. Geological Survey, private consultants, universities, and private and commercial river runners and guides.

The objectives of the GCES were 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 water delivery requirements, that would improve or better protect the environmental and recreational resources?**

C. The Glen Canyon Environmental Studies Final Report and Technical Reports.

Information gathered by the GCES is presented in the Glen Canyon Environmental Studies Final Report and its four appendices (Sediment Report, Biology Report, Recreation Report, and Operations Report). A summary of the final report is presented as Section II of this report. Additional information and analyses may be found in the individual technical reports. Executive Summaries of these technical reports are presented in the following four sections: Section III: Sediment Reports, Section IV: Biology Reports, Section V: Recreation Reports, and Section VI: Dam Operation Information.

D. How To Obtain the Reports

The Glen Canyon Environmental Studies Final Report and the technical reports are available to the public through the U.S. Chamber of Commerce at:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone (703) 487-4650

To obtain any of the Glen Canyon Environmental Studies reports, either phone or write the National Technical Information Service (NTIS). Request the report by the NTIS Accession Number and verify the current price. Prices for paper copies vary and range from $9.95 to $36.95 for 1-500 pages, plus shipping and handling. Foreign prices are somewhat higher. Microfiche copies (a 4 X 6 inch sheet contains up to 98 pages of text and is priced at $6.95) are also available. A Telecopier or Facsimile Service is also available by calling (703) 321-8547, or by Telex by contacting 89-9405 (Domestic) or 64617 (International). Payment may be made by check, money order, or major credit card.

Complete library sets of the Glen Canyon Environmental Studies Final Report and technical reports are also available at the following locations:

Bureau of Reclamation
Upper Colorado Region
125 South State Street
Salt Lake City, UT 84147
phone (801) 524-5302

National Park Service
Grand Canyon National Park
Div. Resources Management
Grand Canyon, AZ 86023
phone (602) 638-7751

U.S. Fish & Wildlife Service
Phoenix District Office
3616 W. Thomas, Ste. 6
Phoenix, AZ 85019
phone (602) 261-4720

In addition, three of the technical reports within the Sediment Section are pending publication as U.S. Geological Survey Professional Papers (Nos. 02 and 05). Three may be obtained as open-file reports (Nos. 02, 03, and 05) through:

U.S. Geological Survey
Books and Open-file Report Section
Federal Center, Building 810
P.O. Box 25425
Denver, CO 80225
phone (303) 236-7476

Seven of the executive summaries are identical to the technical reports. These are GCES Report Numbers 04, 06, 13, 26, 29, 32, and 33.

Section II: Glen Canyon Environmental Studies Final Report

SECTION II: GLEN CANYON ENVIRONMENTAL STUDIES FINAL REPORT

GCES REPORT NO. 01: NTIS ACCESSION NO. PB88-183348/AS

GLEN CANYON ENVIRONMENTAL STUDIES
FINAL REPORT

SUMMARY AND PRINCIPAL CONCLUSIONS

This report was prepared by individuals representing the following:

Bureau of Reclamation
Geological Survey
Arizona Game and Fish
National Park Service
Fish and Wildlife Service
Private Consultants

INTRODUCTION

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. This study was not intended nor designed to lead directly to changes in dam operations. 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.

OBJECTIVES

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.

RESULTS AND DISCUSSION

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 re-deposited 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>

CONCLUSIONS

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.

Section III: Sediment Reports

SECTION III: SEDIMENT REPORTS

DEBRIS FLOWS FROM TRIBUTARIES OF THE COLORADO RIVER GRAND CANYON NATIONAL PARK, ARIZONA

Debris flows, slurries of clay- to boulder-size particles, are a major process of sediment transport to the Colorado River from ungaged tributaries in Grand Canyon National Park, Arizona. Debris flows are runoff events of large magnitude and short duration that occur infrequently. They are the source of potentially large volumes of sand for beaches on the Colorado River. By forming debris fans at tributary mouths, these flows create and modify hydraulic controls (rapids) on the Colorado River.

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INTRODUCTION

A potentially large source of sand for Colorado River beaches in Grand Canyon National Park, Arizona, is derived from sediment transported from small tributary drainages (Figure 1). Little is known about the annual sediment yield from these drainages, and existing methodology for predicting sediment yields from small basins is not designed for high-relief basins with a large potential for slope failures. The key to estimating sediment transport is an understanding of the sediment transport process.

A previous flood report (Cooley et al. 1977) and recent mapping of alluvial deposits in tributary canyons during this project indicate that debris flows are the dominant process of sediment transport in small drainages in Grand Canyon National Park. Debris flows are common in arid and semiarid regions, but their importance in supplying sediment to the Colorado River has not been previously recognized. The purpose of this report is to document the occurrence of debris flows in Colorado River tributaries and to study three tributary canyons in detail for debris-flow frequency and the magnitude of recent events.

METHODS

Debris flows are flowing water-based slurries of poorly sorted clay- to boulder-size particles (Costa 1984). Debris flows typically have volumetric water content of

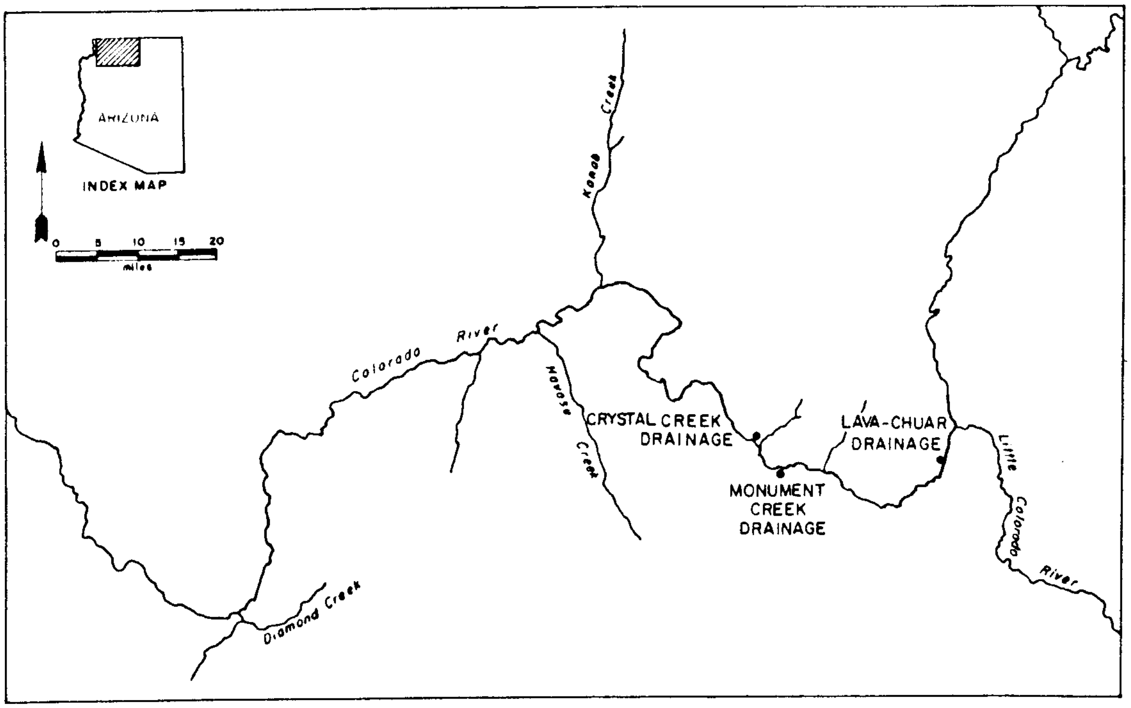

Figure 1. Map of the Colorado River through Grand Canyon National Park with location of the study sites.

15-40 percent compared with 40-80 percent for hyperconcentrated flow and 80-100 percent for streamflows (Beverage and Culbertson 1964). Debris-flow deposits were identified in tributary canyons on the basis of poor sorting of particle sizes, lack of sedimentary structures, and matrix support of cobbles and boulders.

During this study, debris-flow deposits were observed in 36 tributaries of the Colorado River. Of these, 21 showed evidence of recent activity. On the basis of previous reports of debris flows, we selected three of these tributaries for more detailed study: Lava-Chuar Creek drainage at River Mile (RM) 65.5, Monument Creek drainage at RM 93.5, and Crystal Creek drainage at RM 98.2. The fieldwork for this project was completed in March and April 1986.

The frequency of past debris flows was determined from analysis of preserved stratigraphy in the tributaries. Sediments from discrete debris flows were traced longitudinally using their characteristic color, lithology, and particle sizes. Radiocarbon dating, analysis of scarred trees, and historical photographs provided a control on dating the ages of events. Evidence for all events, however, has not necessarily been preserved in the tributaries. We therefore estimated the minimum frequency of debris flows.

Simplified hydraulic formulas were used to calculate flow velocities and discharges for debris flows (Pierson 1985). We calculated velocities from runup evidence of the velocity head, which is preserved in sites where an obstacle is oriented perpendicular to the flow direction. Superelevation evidence, which is found where the flow surface is elevated on the outside of bends due to centrifugal forces, was also used to calculate velocities. The methods provide a conservative estimate of the actual velocity of debris flows (Pierson 1985). Discharge was calculated as the product of velocity and cross-sectional area. Project personnel collected 5- to 10-pound samples of debris-flow matrix in order to reconstitute the water content of the debris flow using methods described in Cooley et al. (1977) and Pierson (1985). Uncertainty in the reconstituted water content by volume for each sample was 1-2 percent. Particle-size distributions were obtained by combining sieve data with point-count data obtained in the field. The two methods yield numerically equivalent particle-size distributions (Kellerhals and Bray 1971).

DEBRIS FLOWS IN THREE TRIBUTARIES

Evidence for at least five prehistoric and three historic debris flows is preserved in the Lava-Chuar Creek drainage. Of the historic debris flows, one occurred between 1916 and 1966, another in December 1966, and the last between 1973 and 1984. Debris flows have reached the Colorado River on an average of every 200 years during the last 1,500 years and every 20-30 years since 1916. Debris flows may reach the Colorado River more frequently now because some prehistoric debris flows may not have overtopped the terraces to leave depositional evidence.

The debris flow of 1966 in the Lava-Chuar Creek drainage began as slope failures in the Permian Hermit Shale and Permian and Pennsylvanian Supai Group and traveled 6.5 miles downstream to the Colorado River. It had a velocity of 12 ft/s and a discharge of about 4,000 cubic feet per second (cfs) near the Colorado River. The average water content of the flow was estimated to be 22.5 percent; hence, the peak sediment and water discharges are estimated to be 3,100 and 900 cfs, respectively. The debris flow was composed of 30-35 percent sand and carried boulders that were about 1-2 ft in diameter. The largest boulder weighed an estimated nine tons.

Two debris flows occurred in the last 25 years in Monument Creek drainage. A storm on July 27, 1984, initiated an avalanche and subsequent debris flow that reached the Colorado River. Some evidence indicates a debris flow occurred in the early 1960s, and still older debris-flow deposits were radiometrically dated at about A.D 1780. Lack of correlation with downstream deposits, however, precluded using this latter date for determining frequency of events.

The debris flow of 1984 in Monument Creek drainage began as an avalanche from the Esplanade Sandstone of the Supai Group 2,000 ft above the channel. A 20-foot-high debris dam resulted and had not been breached as of 1986. The debris flow traveled 2.8 miles to the Colorado River at a velocity of 11-13 ft/s and had a peak discharge of about 3,800 cfs. The water content of the flow ranged from 27-34 percent, and the sand content from 30-40 percent. One boulder that was transported during the flow weighed an estimated 37 tons.

This flow created a new fan surface at the Colorado River that significantly constricted Granite Rapid. We estimated volume of the sediment transported onto the fan and into the river on the basis of four hypothesized scenarios of the fan geometry after deposition of debris-flow sediments. The most likely volume of sediment transported onto the fan and into the river is 300,000 cubic feet. In 1986, the debris fan was completely devoid of particles smaller than 16 mm in diameter, which suggested that all finer particles (including sand) were transported quickly into the Colorado River. Assuming an average sand content of 35 percent, the estimated volume of sand entering the river is 84,000 cubic feet, with a range for all scenarios of 56,000-150,000 cubic feet. Estimates of the volume of transported sediment and the upstream discharge indicate that the fan was created in 1-3 min during the first pulse of the debris flow.

The Crystal Creek drainage has averaged a minimum of one debris flow reaching the Colorado River every 50 years. A large flow in December 1966 (Cooley et al. 1977) has been the only one to reach the Colorado River in this century. Small debris flows that did not reach the Colorado River significantly aggraded the channel and deposited sediments that probably caused larger debris flows to reach the river.

The debris flow of December 1966 began with 11 slope failures in the Hermit Shale and Supai Group and traveled 13 miles to the Colorado River. Calculated flow velocity ranged from 10-18 ft/s, and the discharge ranged from 9,200- 14,000 cfs. Water content of the debris flow ranged from 24-33 percent, and sand content from 10-15 percent. One boulder transported by the flow weighed an estimated 47 tons, and boulders with diameters in excess of 5 ft were common. Upon reaching the Colorado River, the debris flow created a new fan surface that significantly constricted the Colorado River (Kieffer 1985).

DISCUSSION AND CONCLUSIONS

Similarities among the three debris flows studied are indicative of the cause and nature of debris flows in Grand Canyon National Park. All three flows were initiated as slope failures in the Hermit Shale and Supai Group, especially the Esplanade Sandstone. All debris flows transported a poorly sorted mixture of clay- to boulder-size particles with water contents that ranged from 23-33 percent by volume. The largest boulders transported ranged from 9 tons in the Lava-Chuar Creek drainage to 37 and 47 tons in the Monument Creek and Crystal Creek drainages, respectively. Two of the three debris flows significantly constricted the Colorado River at the tributary mouths. The frequency of debris flows reaching the Colorado River is tentative; however, available data suggest that one debris flow reaches the Colorado River every 20-50 years in these drainages. A compilation of historical information on flow events from Grand Canyon tributaries, however, indicates that debris flows occur more frequently throughout the park.

The bedrock geology of Grand Canyon National Park provides an ideal situation for the initiation of debris flows. The high relief combined with differential strength properties of the rocks results in a high potential for slope failures. The most common source of mobilized sediments for debris flows are the Hermit Shale and Esplanade Sandstone. Other sources include the Permian Kaibab Limestone, Toroweap Formation, and Coconino Sandstone; the Cambrian Muav Limestone and underlying Bright Angel Shale; and Quaternary basalts in the western Grand Canyon. Dispersive and swelling clays in some of these formations aid in the initiation of debris flows.

The magnitude and frequency of debris flows control the hydraulics of the Colorado River in Grand Canyon National Park. Debris flows from small tributaries aggrade fans that typically force the river against the opposite wall of the canyon (Figure 2). The ability of small drainages, such as Monument Creek, to form hydraulic controls (rapids) on one of the largest rivers in the United States is hydrologically significant. The debris fans also cause flow separation zones conducive to deposition and storage of sand on beaches. Reworking of debris fans by discharges of the Colorado River creates secondary riffles or rapids (Figure 2). Debris flows are the source of large volumes of sand entering the river at discrete points, although the debris flows occur infrequently. Knowledge of the magnitude and frequency of debris flows is necessary for any understanding or long-term estimates of sediment transport in the Colorado River in Grand Canyon National Park.

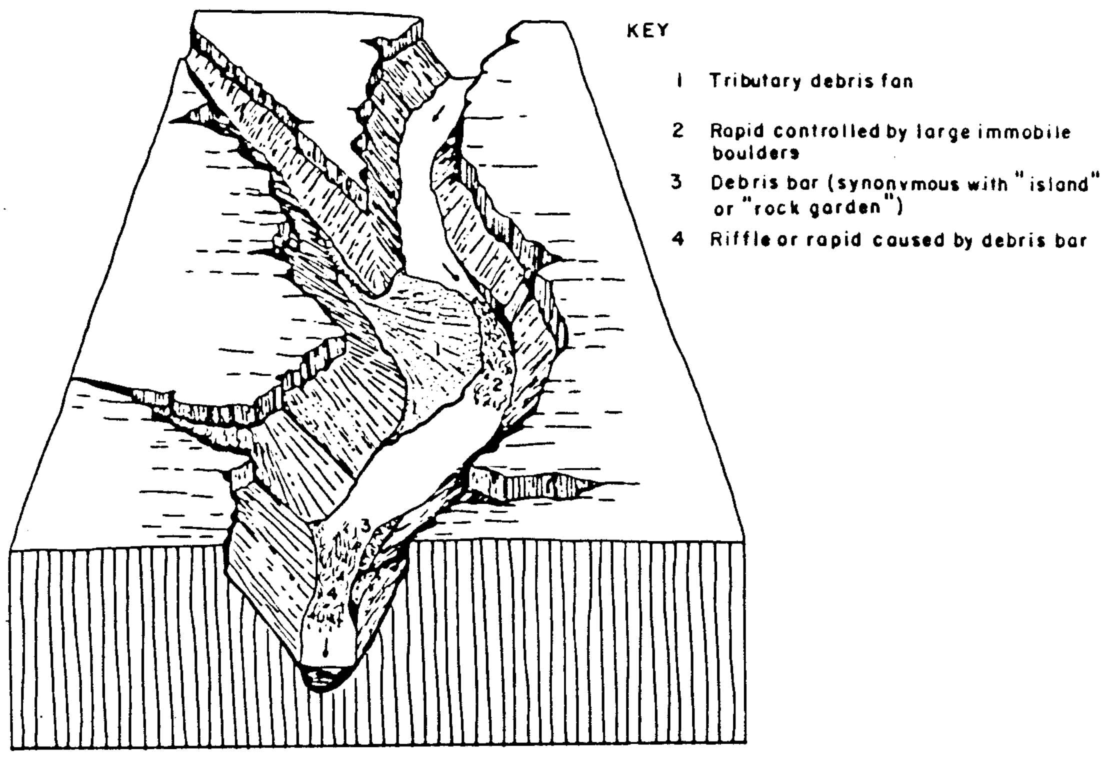

Figure 2. Geomorphic features of a typical rapid controlled by debris flows on the Colorado River.

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THE RAPIDS AND WAVES OF THE COLORADO RIVER GRAND CANYON, ARIZONA

The hydraulics and geomorphology of 12 rapids on the Colorado River are described in this report, on a 20-min VHS videotape[1] (U.S. Geological Survey [USGS] Open File Report 86-503), and on ten hydraulic maps (USGS Miscellaneous Investigations map I-1897, parts A-J).

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INTRODUCTION

Each rapid of the Colorado River is unique, but the major rapids have many hydraulic features in common. In this report, I describe the general features of 12 of the major rapids of the river in Marble Canyon and Grand Canyon, and address the following topics: (1) definition of the hydraulic and geomorphic features at rapids; (2) location of the rapids in terms of geologic structures of the Colorado Plateau; (3) channel geometry and hydraulic structures; (4) causes of rapids, pools, and scour holes; (5) a generalized hydraulic model for rapids; (6) hydraulic nature of pools and backwaters; (7) hydraulic nature of tongues and lateral waves; (8) breaking waves in the rapids; (9) behavior of water near large rocks within rapids; (10) movement of boulders and erosional contouring of the river channel at rapids; (11) the relation of rapids to rock gardens below them; and (12) minor effects, such as curvature of the river at rapids.

OBJECTIVES

Work on the Colorado River by Howard and Dolan (1976), related work by Graf (1980) on similar rivers, and preliminary work done at Crystal Rapid by Kieffer in 1983 (Kieffer 1985) has demonstrated that Grand Canyon rapids have changed since Glen Canyon Dam was closed in 1963. Data on the shape of the river channel and the material that lines it are conspicuously absent and are needed before response of the rapids to discharges

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[1] The video may only be obtained by requesting it from the author (U.S. Geological Survey, 2255 Gemini Drive, Flagstaff, Arizona 86001.

through the dam can be predicted. The objective of this study was to obtain data on the configuration of the channel of the Colorado River in the vicinity of the rapids and on the hydraulics of the river in the rapids.

METHODS

Twelve major rapids were selected for study: House Rock, 24.5 Mile, Hance, Cremation[2], Bright Angel[2], Horn Creek, Granite, Hermit, Crystal, Deubendorff, Lava, and 209 Mile. These rapids include the largest on the river, and are of interest for hydraulic, sediment transport, beach stability, and recreational safety studies. 209 Mile Rapid was not studied in detail, and Cremation Rapid and Bright Angel Rapid are treated as a single reach of the river; therefore, ten rapids were studied in detail and mapped.

Two river trips of 16-18 days duration were conducted for the purposes of: (a) filming time-lapse photography of the rapids as discharge varied during fluctuating flow from about 7,000 cubic feet per second (cfs) to about 20,000 cfs, (b) surveying control points to provide data for constructing topographic maps by cartographic methods, (c) recording fathometer data across the channel above the rapids, (d) launching floats and filming their trajectories through the rapids for analysis of streamlines and velocity, and (e) obtaining preliminary data on the size distribution of the large boulders lining the channel of the river. Because travel time between the rapids is substantial, even in a motor boat, the average time spent at each of the ten sites was only two days.

RESULTS

Most data obtained in this study are presented on ten hydraulic maps of the rapids (USGS Miscellaneous Investigations Map I-1897, parts A-J). The maps are at a scale of 1:1,000 (except for the map of the river in the vicinity of the Grand Canyon gaging station for which a scale of 1:2,000 was used because of the large

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[2] These two rapids do not have formal names. The names in this report are used informally to indicate the two rapids in the vicinity of the USGS's Grand Canyon gaging station.

area covered). Each map shows: (a) a description of the rapid; (b) topographic contours (metric contour intervals of 1 and 0.5 m) of the channel; (c) hydraulic information at 5,000 and 30,000 cfs and, where information is available, at 92,000 cfs; (d) water surface elevations; (e) velocity and streamline data at one or two discharges; and (f) approximately five channel cross sections. Three parts of one map (for House Rock Rapid) are attached as Figures 1, 2, and 3.

DISCUSSION

Debris flows from tributary canyons constrict the main channel episodically, and then floods of differing sizes on the Colorado River widen the constrictions and move material from the debris fans downstream into secondary features referred to as "rock gardens." The shape of the Colorado River channel in the vicinity of the debris fans depends on the relative frequencies of tributary and mainstem floods, on the nature of the material brought into the channel by the tributary floods, and on the competence of the Colorado River. Prior to closure of Glen Canyon Dam in 1963, natural floods had contoured the river channel through the debris fans into remarkably uniform shapes, for which the ratio of narrowest channel width to average channel width (the "constriction") was about 0.5 (Figure 4).

Figure 4 is a histogram showing the ratio of river width in the most tightly constricted part of a rapid to an average unconstricted channel width. Data are for 59 of the largest debris fans in the 250-mile stretch below Lees Ferry. These debris fans are probably 1,000-100,000 years old, except the debris fan at Crystal Rapid, formed in 1966. Data are based on the widths of the surface water in the channel on 1973 aerial photos. Crystal Rapid in 1973 is represented by the highly constricted data point on the left. The surface constriction was 0.33; the average channel cross section constriction was probably about 0.25.

Figure 1 (below) is a hydraulic map of House Rock Rapid, Grand Canyon, Arizona (River Mile [RM] 17). North is to the left; the water is flowing from left to right. The channel of the river occupied by pre-dam discharges extends approximately up to the 925 m contour level. The channel below the discharge of 5,000 cfs, shown here, cannot be mapped; however, some fathometer data were obtained to allow estimates of channel depth below the levels filled by a discharge of 5,000 cfs. The contours were compiled from aerial photographs flown by the U.S. Bureau of Reclamation during the Glen Canyon Environmental Studies, with control points surveyed by the author. The contour interval is 1 m (solid lines) or 0.5 m (dashed lines). The hydraulic structure of the water and important features of the channel bottom are shown by air brush illustration. The boat on the lower left is 33 ft in length, and is shown only for scale. Like all of the major rapids in the Grand Canyon, House Rock Rapid is formed by constriction of the river channel by debris from a side canyon (Rider Canyon enters from the west, at the bottom of the figure). The area covered by diagonal pattern is a sandy beach formed by deposits from the eddy in the lower right corner of the figure. Diagonal lines in the opposite direction indicate vegetation.

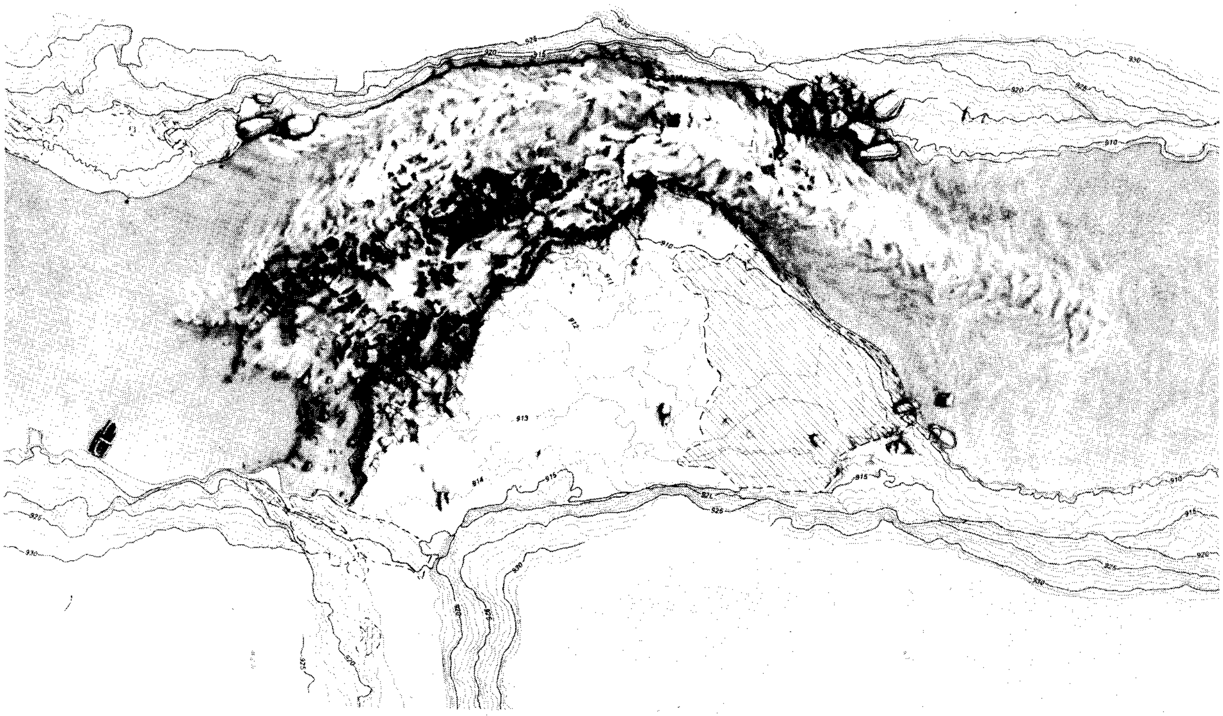


Figure 2 (below) shows streamlines of flow through House Rock Rapid, and velocities along the streamlines (in meters per second [m/s]). The streamlines were determined from floats launched upstream of the rapid. Their trajectories were filmed from the camera station indicated, and the velocities were determined by measurement of the trajectories and elapsed time on the films. The velocities increase from about 0.5 m/s (1.6 ft/s) in the backwater upstream of the rapid (not shown on this figure), to about 2.5 m/s (8.2 ft/s) at the head of the rapid, to 6-7 m/s (19.7-23.0 ft/s) in the narrowest part of the rapid, and then back to about 4.5 m/s (14.8 ft/s) in the jet that emerges next to the eddy and beach downstream of the rapid. The velocities of 6-7 m/s (19.7-23.0 ft/s) in the constriction here appear typical of the rapids measured (to the date of this report, velocities have been measured in Lava Falls and Hance Rapid at approximately 7,000 cfs, and in Horn Creek Rapid at 17,000 cfs in addition to House Rock). These velocities are among the highest velocities ever measured on a river.

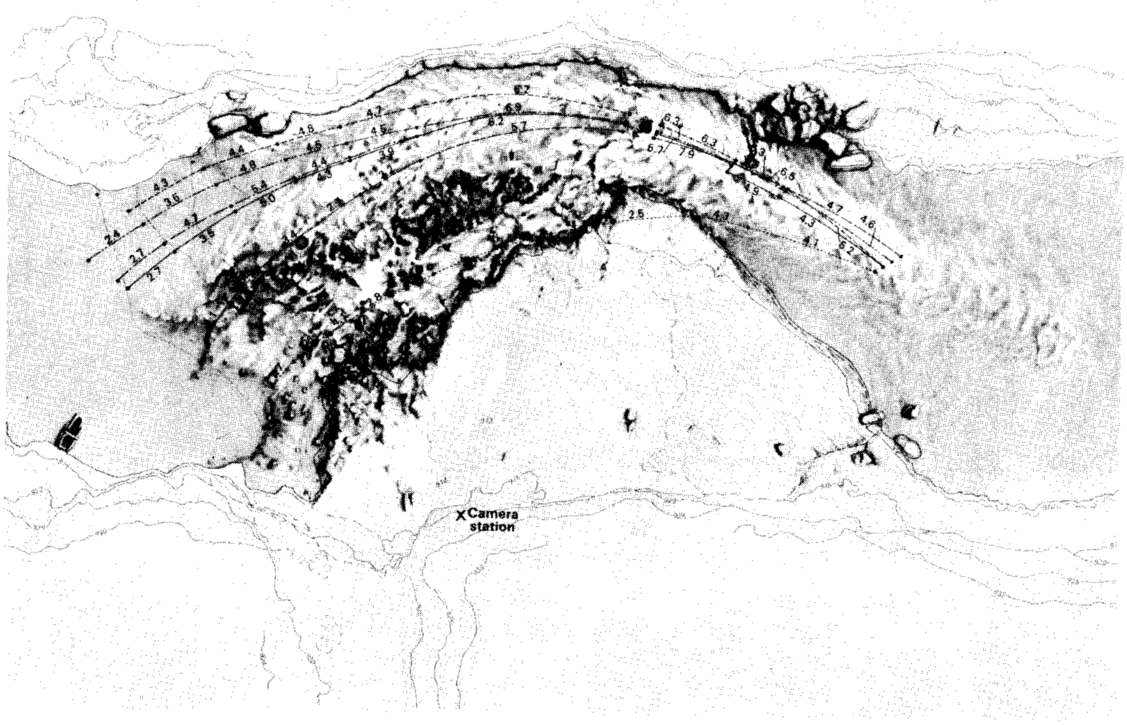
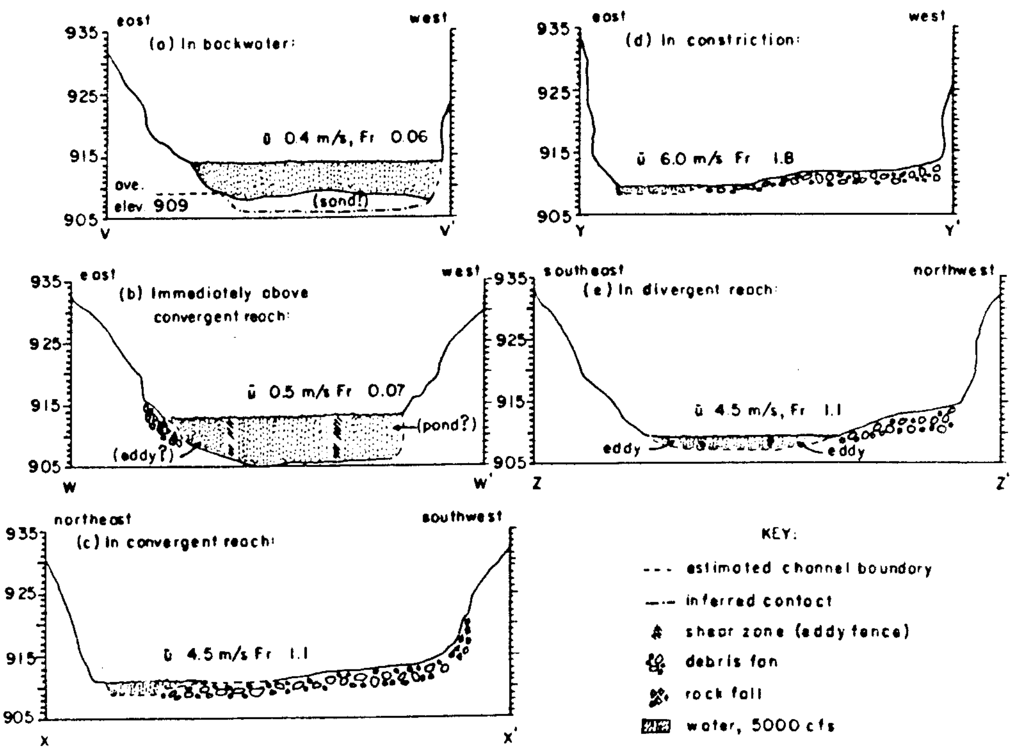


Figure 3 (below) illustrates cross sections through five parts of House Rock Rapid. Note the dramatic change in cross-sectional area of the flow in the different parts of the rapid, reflecting differences of more than one order of magnitude in average flow velocity, u (shown on each cross section) within the rapid. The Froude number (Fr, also shown on each cross section) is a characteristic dimensionless number that indicates the relative importance of kinetic and potential energy. The Froude number is very small (approximately 0.05) in the backwater, indicating that nearly all of the energy of the water is stored in potential energy (i.e., depth). The Froude Number increases to unity in the convergent reach and reaches a value of nearly 2 in the most tightly constricted part of the rapid where the flow is shallowest. In this section, the flow is supercritical, and the kinetic energy of the water is more important in determining the flow dynamics than is the potential energy. Standing waves are stable in supercritical flow, and these waves are the major hydraulic features of the rapids. The flow decelerates to Froude Number unity in the diverging section of the rapid near the downstream eddy.



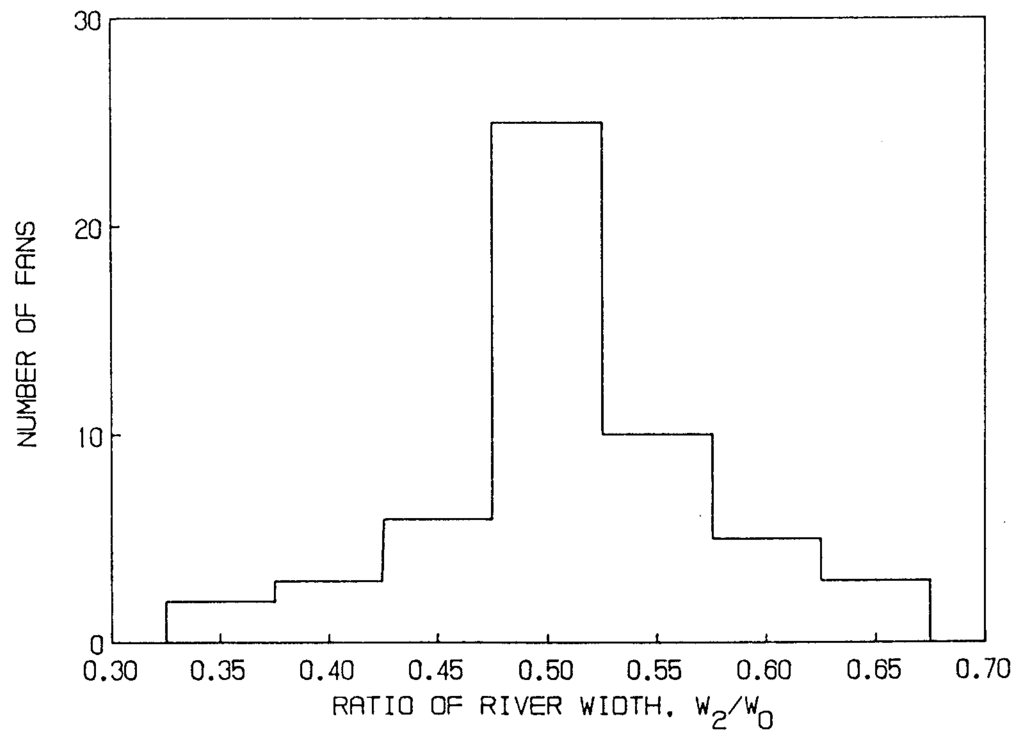


Figure 4. Ratio of river width in the most tightly constricted part of a rapid to an average unconstricted channel width upstream of the rapid.

In the first decade after dam closure, 27 percent of the tributary fans had built outward because of tributary flooding; 10 percent had built outward by more than 49 ft (Howard and Dolan 1976). In the additional 12 years until 1986, severe changes (defined here to involve emplacement of boulders on the order of 3 ft diameter into the main channel occupied when discharges are less than 30,000 cfs) have occurred in enough of the tributary canyons to lead us to believe that, on the time scale of decades, major changes will take place in the rapids.

Median, mean, and peak discharges through the Grand Canyon have been significantly altered by the construction and operation of Glen Canyon Dam (Dolan et al. 1974). Maximum powerplant discharges are about 30,000 cfs and, prior to the filling of Lake Powell to operational level, these discharges were generally not exceeded. Only since 1983 have the peak discharges (up to 92,000 cfs) approached the pre-dam annual spring flood levels (80,000 to 125,000 cfs). The large, rare floods that widened the river channel in the vicinity of the debris fans (estimated by Kieffer [1985] to have been as large as 400,000 cfs) no longer occur. Therefore, for discussion of the rapids, it is convenient to think of the dam discharges during three periods: (a) pre-dam, (b) prior to filling of Lake Powell to operational level (1962-1983), and (c) after filling of the lake (1983 to future).

The velocity and streamline data obtained in this study suggest that boulders on the order of 3 ft diameter can be moved from the main channel at even low discharges (e.g., from considerations of the Hjulstrom criterion for boulder transport and unit stream power of the river, the velocities of 20-25 ft/s measured at 5,000 cfs at House Rock Rapid [Figure 2] are adequate to move 3 ft boulders out of the narrowest part of the channel at that location). The competence of the river, even at relatively low discharges, approaches that of some of the largest floods in the world inferred from paleohydraulic reconstruction (e.g., Baker 1984). For the Colorado River, then, we have the opportunity both to use paleohydraulic knowledge to constrain our models where the scale of time and space are both too large for laboratory study, and to contribute to the understanding of rare geologic events in the past by monitoring and understanding of this large and powerful river.

At Crystal Rapid, the powerplant discharges from 1966 to 1983 cut only a relatively narrow channel through the debris fan. In its narrowest part, the channel was only about one-quarter the width of the unconstricted channel upstream of the rapid. This single example suggests that, if discharges were held to powerplant releases, the rapids would become severely constricted with time, and that the river channel would be approximately twice as constricted as in pre-dam time.

Discharges larger than powerplant releases will widen the river channel back toward the pre-dam geometry of the channel. The 1983 high water of 92,000 cfs enlarged the constriction at Crystal Rapid from a value of approximately 0.25 to approximately 0.40. Extrapolation of the calculations for Crystal Rapid to higher discharges suggests that floods on the order of 400,000 cfs have contoured the channel of the Colorado River to its present shape at the older debris fans (Kieffer 1985). Spring releases of 50,000-60,000 cfs and 1983-level releases of 100,000 cfs will widen severely constricted places (e.g., a constriction of 0.25 might be enlarged to 0.40 by a release of 92,000 cfs). However, unless releases approach 300,000-400,000 cfs the rapids will eventually become more constricted than they were prior to Glen Canyon Dam closure.

Navigation through the rapids appears to be at the limit of safety when the channel is narrowed much beyond the pre-dam widths (viz., Crystal Rapid is the most difficult rapids on the river because it is so tightly constricted). The tightly constricted rapids are difficult because of the standing waves that are stable within supercritical flow. The amplitude and position of these waves can change as discharge changes, particularly during discharges when a new debris fan is being modified by erosion of the river channel. An example of such changing waves occurred at Crystal Rapid during the high releases of 1983 (Kieffer 1985).

As the discharge rose beyond the powerplant release maximum of about 30,000 cfs to about 60,000 cfs, a standing wave 15-20 ft in height stood across most of the flow and caused several boating accidents (Figure 5). This wave was a hydraulic jump caused by the severe constriction at Crystal Rapid. As the discharge rose toward 92,000 cfs, flow velocities were high enough to cause widening of the channel and a lessening of the height of the wave, but, because the channel of the river at Crystal Rapids is still more tightly constricted and steeper than at rapids where large natural floods have occurred, this remains a difficult rapid for navigation.

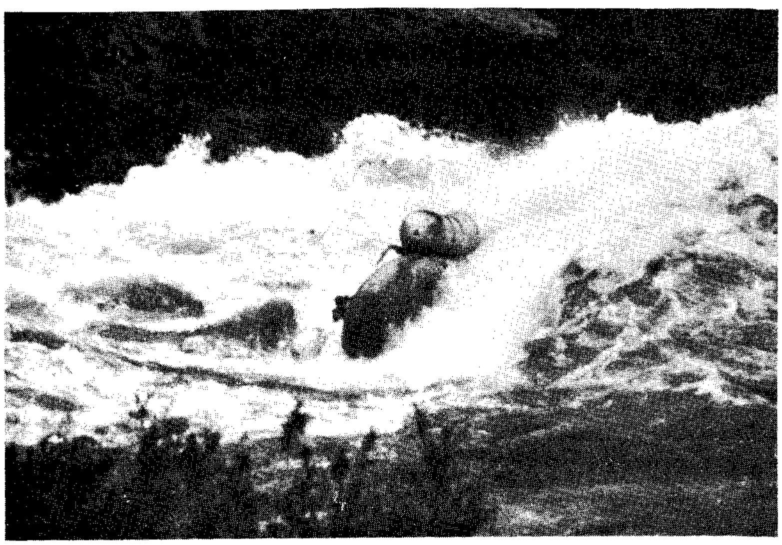


Figure 5. A motor boat 15 ft in width in Crystal Rapid in 1983. Photograph courtesy of Richard Kocim.

RECOMMENDATIONS FOR OPERATING CRITERIA

Operation of Glen Canyon Dam should take into account the effects of releases on the rapids in the following three ways: (1) navigability of the rapids, (2) safety of passengers in the rapids, and (3) geologic evolution of the rapid-debris fan relations.

Low flow conditions could affect navigability and safety. The larger boats cannot get through several of the rapids (e.g., Horn, Hance) at discharges below about 5,000 cfs (exact determination of this discharge was not in the scope of this report, but could be determined from river-rafting companies). Therefore, the lowest discharges may have to be voided from this consideration.

Passenger safety is determined largely by the strength of the waves. Additional observations on this subject can be found in the GCES-sponsored U.S. National Park Service studies of boating safety. Safety conditions will be variable for each rapid at different discharges and will change as tributary debris flows modify the rapids.

Finally, managers should recognize the fact that discharges through Glen Canyon Dam can be sufficiently high to erode the river channel if it becomes constricted by fresh debris flows. This fact should be considered both if large spills are needed, or as a management option for purposeful modification of the rapids. The schematic diagram of Figure 6 illustrates the processes that should be examined.

Assume, for simplicity, a simple unconstricted channel of width w_1, as in Figure 6a. A debris flow or flash flood from a side canyon fills the channel, causing water to pond upstream of the debris dam (Figure 6b). Water from this temporary pond cuts through the debris dam, usually at its distal end, creating a narrow channel. This breach of the debris dam probably occurs within hours or days of the side canyon flood. Low discharges, e.g., typical of the powerplant releases of 5,000 to 30,000 cfs, cut a relatively narrow channel (Figure 6c). The rocks eroded from the narrow channel in the debris fan are carried downstream in the high velocity flow of the constriction, and deposited in and below the diverging section in the features known as "rock gardens," shown in Figure 6 by XXXX. Strong hydraulic jumps (HJ) exist in the supercritical flow regime in the rapids and form the waves of the rapids. Large floods further widen the channel (Figure 6d).

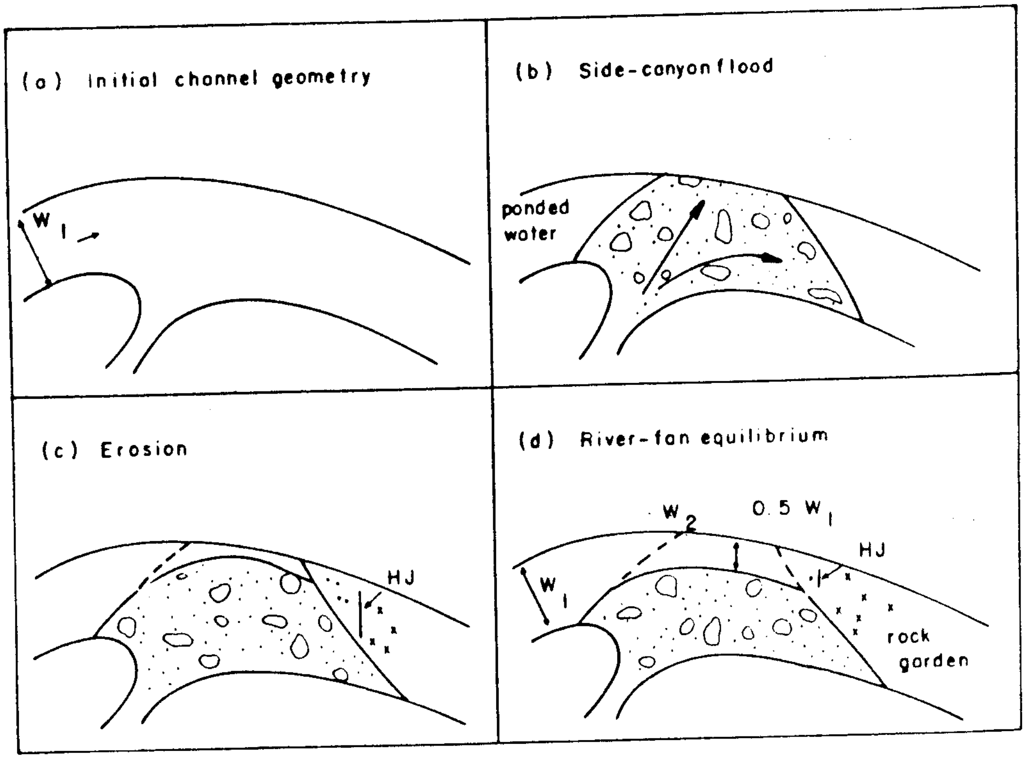


Figure 6. Processes involved in contouring the river channel at rapids.

Pre-dam floods, estimated to have reached 400,000 cfs would cut their channel to a width w_2 in the constriction that is about 0.5 of the unconstricted width, w_1. The 92,000 cfs releases in 1983 enlarged Crystal Rapid from a constriction of 0.25 eroded by powerplant releases from 1966-1983 (as schematically shown in part c) to a constriction of 0.40. This rapid is still more tightly constricted than it would be if natural floods (up to about 400,000 cfs) occurred. This tight constriction is the major reason that Crystal Rapid is more difficult than the other rapids for navigation.

Erosion began at Crystal Rapid at discharges on the order of 60,000 cfs (plus or minus 10,000 cfs). At different rapids, erosion could begin at greater or lesser discharges depending on several factors (including constriction, debris size, and river head). High discharges from the dam will be especially effective at modifying the river channel if peak discharges from the dam coincide with natural floods of the Little Colorado River. Therefore, consideration should be given to the consequences of any "substantial" change of discharge at a rapid that has been newly modified by a major tributary debris flow (the meaning of "substantial" in cfs will depend on the particular circumstances at the rapid and cannot be specified a priori).

Recommendations for further work on the rapids include: (1) obtaining flow velocity and streamline data on the rapids cited here at discharges not available during the single year of this study (FY-'86), (2) flying high-resolution aerial photos if discharges above 60,000 cfs are released, (3) field documentation of hydraulics and channel characteristics at any unusually high (approximately 100,000 cfs) or unusually low (approximately 1,000 cfs) discharges, (4) scaled laboratory modeling of flow in rapid-eddy systems, (5) theoretical hydraulic analyses using the data obtained on channel geometry and roughness, and (6) extension of the work performed here to any rapids deemed to be at high-risk for tributary flash floods.

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SONAR PATTERNS
OF THE COLORADO RIVERBED IN
THE GRAND CANYON

Distinctive patterns on side-scan sonar charts and depth-finder charts were used to delineate smooth bottom, sediment waves, and boulders and bedrock outcrops on the bed of the Colorado River in the Grand Canyon, Arizona.

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INTRODUCTION

The sand banks and bars, locally called "beaches," along the Colorado River in the Grand Canyon, Arizona, are composed of sand that is both deposited and eroded by the river. The riverbed serves as a reservoir of sand that is available to be transported to the beaches. This sand is one component of the movable sediment carried by the river. During floods, large volumes of sediment enter and are transported by the river. During sustained flow, material on the riverbed is sorted and redistributed. Although small boulders and cobbles move during floods, sub-rounded to well-rounded gravel and sand constitute the movable sediments at lower sustained discharges.

In this study, distinctive patterns on side-scan sonar charts and depth-finder charts were used to delineate the distribution of movable sediment that forms parts of the Colorado riverbed. We collected bed material samples to provide a qualitative description of the sediment and calibration of bed material to side-scan sonar patterns. This study resulted in a set of 189 sonar-pattern maps, covering about 75 percent of the 225 miles of river from Lees Ferry to Diamond Creek. The gaps resulted from poor or no sonar image in rapids or places where the flow is highly turbulent, and from removal of the sonar fish from the water through major rapids. The maps and data are part of the input to the sediment transport model used by the U.S. Bureau of Reclamation and the U.S. Geological Survey (USGS) to define the movement of sediment through the canyon.

The USGS performed the first detailed survey of the Colorado River in the Grand Canyon in 1923 using alidades and plane tables (Birdseye 1923). They produced maps showing river miles below the USGS gage at Lees Ferry and profiles of the water surface adjusted to a discharge of 10,000 cubic feet per second (cfs). Water-surface profiles were adjusted by discharge because the stage commonly changes more than 10 ft in response to changes in discharge. Leopold (1969) made the first systematic measurements of river depths in 1965. He measured depths approximately every 0.1 mile using a nonrecording depth finder at a discharge of about 48,000 cfs. His locations were from aerial photographs and his mileage from the 1923 USGS river maps. Leopold described scour holes and discussed their formation by high-velocity, downward-directed flow below rapids. In 1975, Dolan et al. (1978) made a continuous-depth profile with a recording Fathometer using the same location methods as Leopold. Their location errors were as great as 0.06 mile. Discharge during their trip was about 16,000 cfs. Howard and Dolan (1981) discussed distribution and transport of sand, cobbles, and boulders by current flow and the change in sediment transport caused by construction of Glen Canyon Dam. They related origin and location of scour holes to both geologic structure and position below rapids and constrictions.

METHODS

Data for this study were collected during three trips on the Colorado River for 225 miles below Lees Ferry (Figure 1). Side-scan sonar images and depth profiles were run concurrently March 1-10, 1984. Discharge during that trip was 24,300 to 25,800 cfs, averaging 25,000 cfs. Cross sections were taken April 28-May 7, 1984, while discharge was 25,500 to 33,200 cfs. Bottom samples were collected September 4-11, 1984, during a discharge of 24,000 cfs. Locations along the river were determined by annotating approximately 1,050 navigation points on aerial photographs taken in 1973 and on recorder charts as data were collected. River miles were assigned to the navigation points on the basis of the 1923 USGS river maps (Birdseye 1923). Probable location accuracy is within 0.03 mile.

A Klein 100-khz side-scan sonar unit was used to acquire sonic images of about 80 percent of the riverbed. The side-scan sonar fish was removed from the water for many of the larger rapids. Images made in or just below rapids or large riffles were unusable, probably because air bubbles entrained in the water absorbed the returning sonic signal.

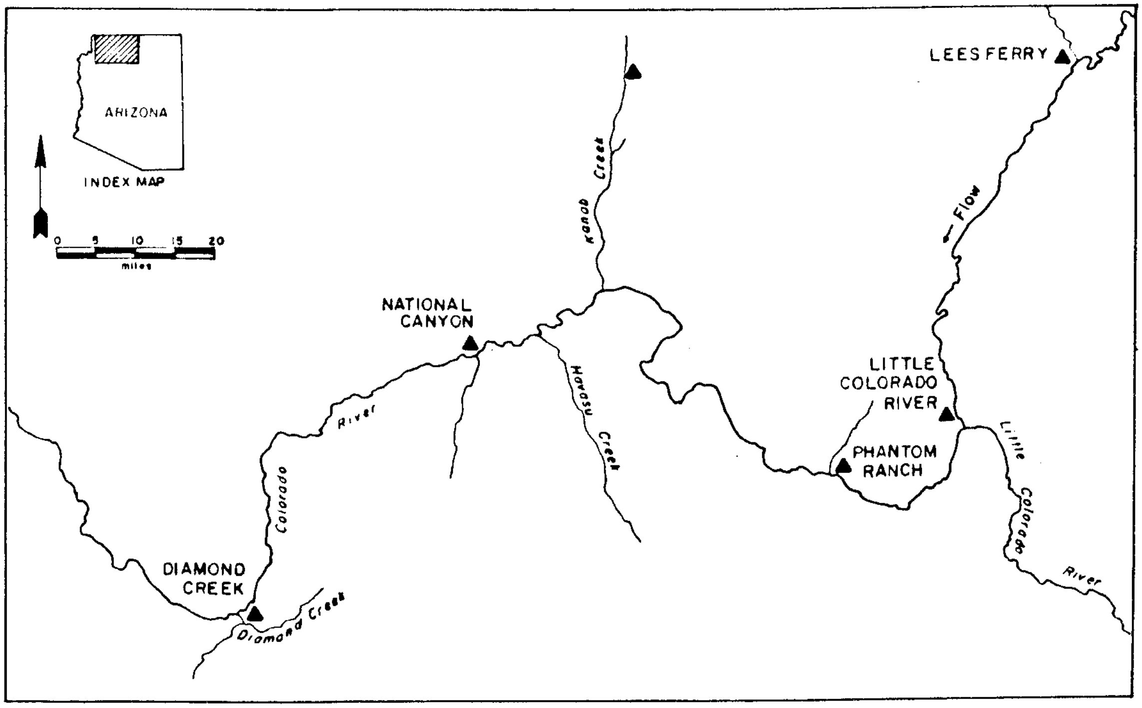


Figure 1. Map of the Colorado River through Grand Canyon National Park (study area).

A Raytheon 208-khz Fathometer was used to record a depth profile of about 95 percent of the river. The profile was taken concurrently with the side-scan sonar data. An attempt was made to measure the depth profile near the thalweg. An assumed sound velocity in water of 4,800 feet per second was used to convert travel time to depth or to distance. Cross sections of the river were taken in pools between rapids or large riffles at 224 locations with the Fathometer and a continuous seismic (subbottom) profiler. The sonic pulse of the profiler was produced by a boomer and had most of its energy concentrated in the frequency range of 900 to 2,000 hz. The profiler was to be used to determine thickness of movable sediment on the riverbed, but poor penetration of the sonic pulses into the sediment resulted in weak returning signals. The signals produced by subsurface layers were commonly obliterated by the strong multiple reflections between the bottom and the water surface.

Fifty bed material samples were taken with a 10-in pipe dredge in order to calibrate patterns delineated on the side-scan sonar charts to the bed material. Sampling depths ranged from 12-64 ft. Quantitative samples of sand and fine gravel and qualitative samples of large pebbles and cobbles were taken by the dredge. Two small boulders were recovered. A typical sample volume was 0.3 to 1.2 cubic feet. At several sites, bed material was not recovered in the dredge, presumably because the riverbed consisted of bedrock outcrops or boulders too large to enter the dredge. Positive contact with the riverbed was made during three sampling attempts before a "no return" was declared. Bed material samples taken with BM-54 samplers at five sediment-collection stations (Figure 1) also were used in calibration of the sonar patterns.

RESULTS

SIDE-SCAN SONAR PATTERNS. A side-scan sonar pattern is produced by multiple sonic reflections from particles and surface features of an area of riverbed. The location and shape of accumulations of movable sediment on the riverbed that produce side-scan sonar patterns are a function of sediment particle size, current-velocity pattern, and length of time a particular velocity pattern has existed. The particles are stored and distributed in an organized way in the sediment accumulations as a result of the variations in local current velocity. Side-scan sonar images on the chart are divided visually into three patterns: B = boulders and bedrock; S = smooth bottom; and SW = sediment waves. See Figure 2 for an example of a side-scan sonar pattern.

Boulders and bedrock outcrops are large in size compared to the resolution of the sonar unit and produce a broken pattern of stripes and spots (pattern B). A diver's observations at a test section above Lees Ferry, BM-54 bed material samples at the Grand Canyon, National Canyon, and Diamond Creek sediment-collection stations (Figure 1), and observations at cross sections indicate that the boulders and bedrock outcrops are commonly covered with a thin layer of sand. The irregular shapes, however, show through the sand to produce the B-pattern. Boulders and bedrock are most extensive along the banks where talus enters the water or bedrock outcrops are exposed. The riverbed of rapids and of the upstream side of scour holes is commonly composed of boulders or bedrock. Boulders form the bed of some riffles. Bedrock outcrops that project above the bottom sediments or large boulders that rest on the riverbed create isolated occurrences of pattern B.

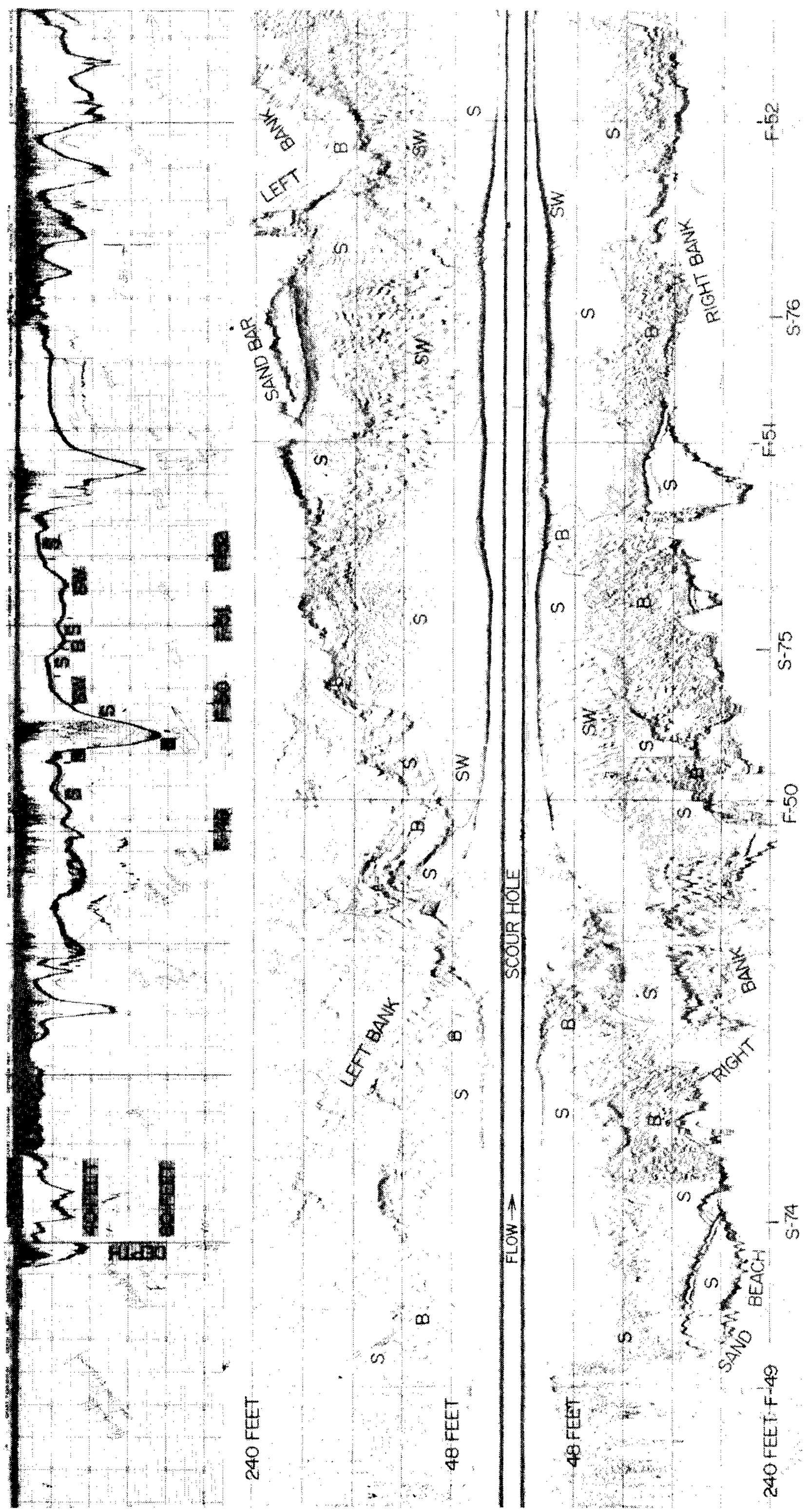


Figure 2. Uncorrected side-scan sonar and Fathometer charts.

Smooth bottom (pattern S) consists of sand, gravel, or cobbles that are smaller than the smallest particle that can be resolved by the sonar unit. The pattern is typically pale, low contrast, and stippled. Pattern S generally is shaded because the return signal gradually increases in strength as the distance from the fish (range) increases. The ripples and irregularities of the riverbed return a stronger signal as the angle of incidence increases. Areas of the bed near exposed sand beaches and bars commonly have underwater cutbanks that show on the sonar charts as bold smooth stripes. These areas are included in the smooth-bottom pattern.

Low-flow aerial photographs taken in October 1984 and dredged bed material samples show that cobble and gravel cannot be reliably distinguished from sand on the side-scan sonar charts. The inability to distinguish between the two bed materials is probably due to the limited resolution and the low dynamic response of the chart paper. In some areas, however, the image does appear to show two types of smooth bottom. An imaging system that would respond to the full dynamic range of the returning signal could probably distinguish sand bottom from gravel and cobble bottom.

Smooth bottom is found near the banks, on the downstream side of scour holes, in some riffles, and in shallow areas just above many rapids. The location of smooth bottom appears to correlate with low current velocity near banks and higher velocity between areas of boulders and bedrock and areas of sediment waves. The sequence of patterns--boulders and bedrock to smooth bottom to sediment waves to smooth bottom to boulders and bedrock--is repeated many times through the canyon. Smooth bottom that extends from low-velocity areas to the beginning of sediment waves probably represents the tranquil-flow transition from plane bed to dunes (Simmons et al. 1961). Smooth bottom near the banks is mainly sand and commonly extends above water where sand bars and beaches are exposed. The aerial photographs taken in October 1984 indicate that smooth bottom in the lower canyon is commonly composed of cobbles. Basalt flows provide an abundant supply of tough cobble- and boulder-size clasts to the river below River Mile (RM) 179.

Sediment waves (pattern SW) are efficient reflectors of sound and produce a strong returning signal. The cyclic alternation of sloping surfaces produces a moderate- to high-contrast striped pattern. The sonar unit resolved sediment waves of amplitudes as small as

0.5 ft, with the largest amplitude observed being 4 ft. Sediment waves are most common near the center of the river in areas of intermediate current velocity and depth. The waves typically begin downstream from short reaches of rising smooth bottom on the downstream side of scour holes and change back into smooth bottom at constrictions or riffles where the depth decreases and current velocity increases. Dredged bed material samples indicate that the sediment waves are composed of medium to very coarse sand, fine gravel, and a few medium to large pebbles. The granules and pebbles show evidence of sustained transport; they are mostly sub-rounded to well-rounded, smooth surfaced, and free from algae or coatings. The fine gravel is probably being transported as bedload. Neither the samples recovered from sediment waves nor the behavior of the dredge during sampling indicated the existence of an armored bottom.

DEPTH PROFILE. The depth profile of the river was taken concurrently with the side-scan sonar images and was used in interpreting the sonar patterns. The Fathometer chart showed sediment waves of amplitude of about 0.3 ft and bottom features of about 0.5 ft in size. The unit commonly showed depths and bed forms in turbulent areas where the side-scan sonar unit produced poor or no records. Profile depths ranged from 5-106 ft at an average discharge of 25,000 cfs. The bottom is irregular in metamorphic rock reaches with near-vertical depth changes of as much as 50 ft.

Scour holes more than 1.5 times deeper than the local mean depth occur below many rapids and riffles. The scour holes are a local feature that owe their location to the high-energy level generated by fall through rapids. Scour is displaced and concentrated below the rapids because the boulder bed of the rapids is resistant (Howard and Dolan 1981). Many of the holes display a characteristic pattern on the depth profile. Rough bottom of boulders and bedrock slopes downward to the scour-hole bottom on the upstream side. Smooth bottom begins in the bottom of the hole or at the base of the downstream side and continues downstream as depths decrease until sediment waves appear. The slope of the downstream side changes smoothly from about one-half the upstream value to 0 (Figure 3). Bed material samples suggest that the bottoms of the holes consist of cobbles and gravel that become finer downstream and change to fine gravel and sand that form sediment waves. Only a small amount of sand is stored in the holes during a sustained discharge of 25,000 cfs. Current velocity in the holes remains greater

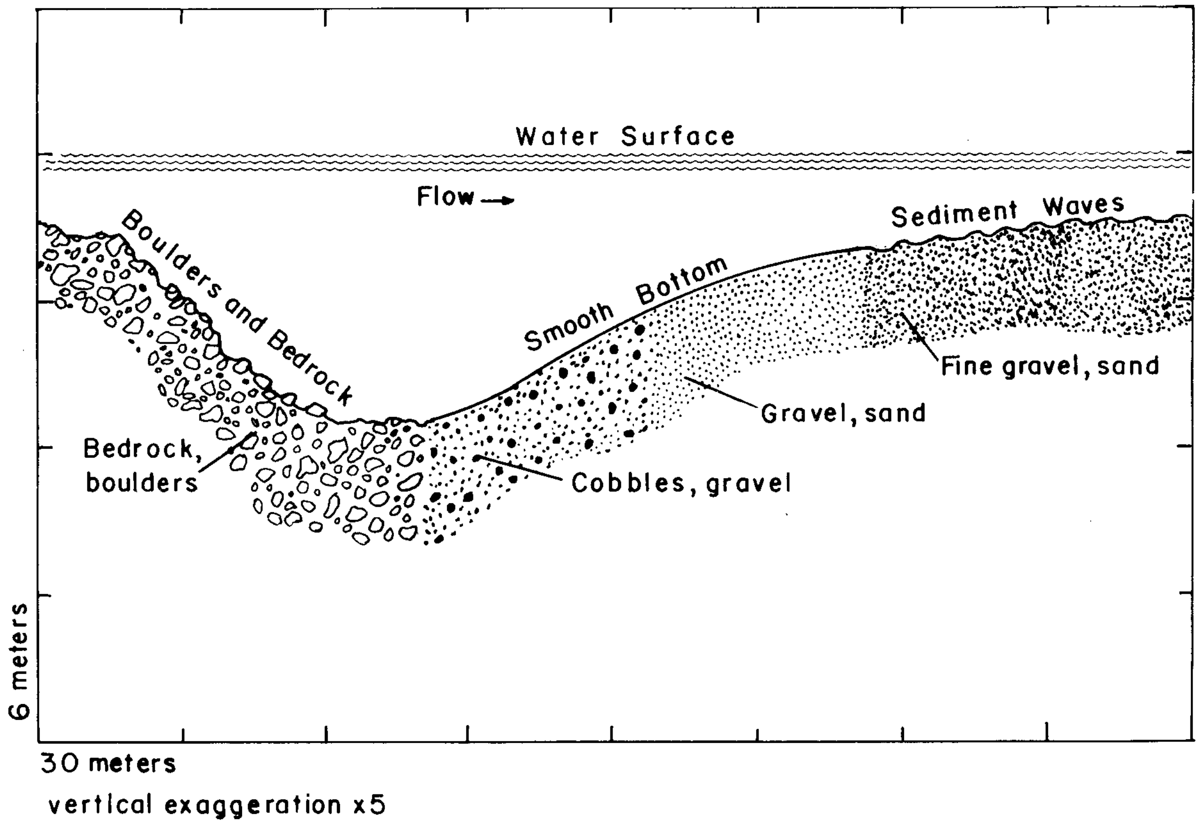
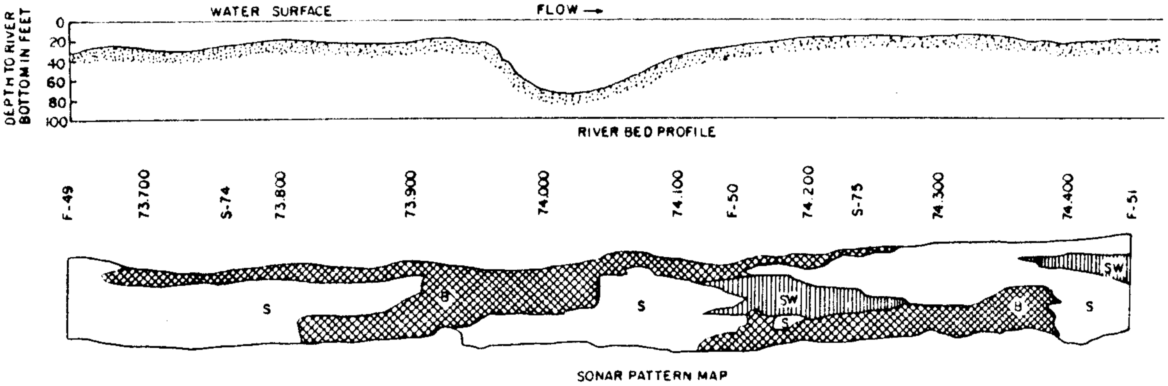


Figure 3. Generalized scour-hole profile, location of side-scan sonar patterns, and bed material.

than in the pools downstream and prevents significant accumulation of sand. The sediment deposited in the hole by a previous flood probably coarsens downward to the point of maximum scour because the particles that accumulate on the bottom become smaller as velocity and discharge decrease during the flood recession.

ANALYSIS AND DISPLAY OF PATTERN DATA. The sonar patterns contain three distortions that must be corrected in order to make geometrically correct maps. A sonar-pattern map derived from part of the uncorrected chart in Figure 2 is shown in Figure 4. The distance axis is traced out by the fish as the boat travels down the river. The plotting position of the distance-coordinate values (miles below Lees Ferry) vary because of changes in boat speed and flow velocity. The digitized distance coordinates were corrected by linear interpolation between navigation points using assigned mileages interpreted from the 1923 USGS maps. Bottom reflections on each side of the fish appear on the range axis of the chart at a point farther than their true position from the distance axis (Figure 5). The



KEY

B,S,SW	Side-Scan Sonar Patterns - B, boulders and bedrock; S, smooth bottom; SW, sediment waves
F-50	Navigation point
74.100	River mile
S-75	Cross Section location

Figure 4. Example of a sonar-pattern map of reach F49F51.

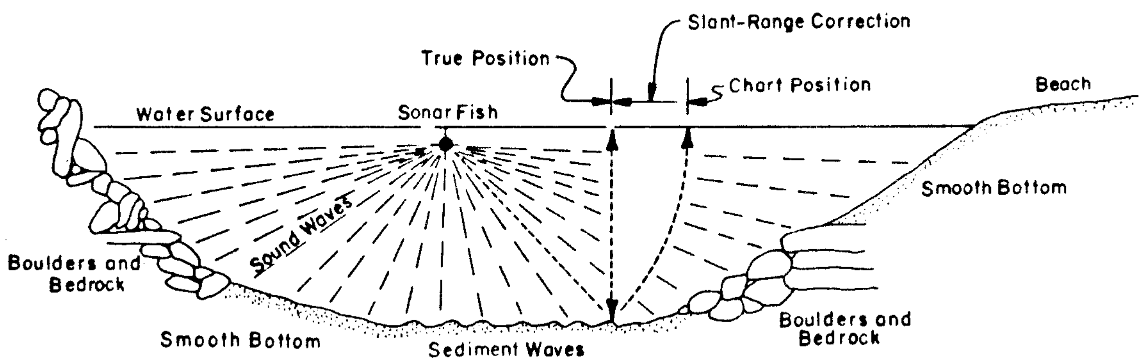


Figure 5. Sonar slant-range correction.

range-coordinate value is decreased by an amount that varies from 0 near the river banks to the distance of the fish above the bottom for reflections directly beneath the fish. The corrections are determined from the depth profile and the bottom and bank slopes. Data from the 224 cross sections are used to estimate the slopes. Generalized cross section geometry and range-correction equations are shown in Wilson (1986). The third correction required is to bend the distance axis to conform to the actual curving course followed by the boat as it traveled down the river. The river generally is narrow with respect to bend radii, and only a few miles of wide meandering channel are present in the canyon. The error in computation of pattern areas caused by this distortion is probably small compared to the errors of range and distance. This third correction was not made and the patterns are plotted and areas are computed using the distance axis as a straight line.

DISCUSSION

Calibrated side-scan sonar patterns can be used to delineate boulders and bedrock, smooth bottom, and sediment waves on the bed of the Colorado River in Grand Canyon, Arizona. The patterns interpreted in this study, however, cannot be used to reliably differentiate sand from gravel on smooth bottom or sediment waves. A 10-in pipe dredge can be used to collect bed material samples of cobbles, gravel, and sand from smooth bottom or sediment waves, but many more samples will be required to define the fraction of sand in movable sediment. Movable sediment during a discharge of 25,000 cfs consists of sand and rounded gravel and forms smooth bottom or sediment waves. Scour holes more than 1.5 times deeper than local mean depth contain cobbles and gravel in and near the bottom; little sand is stored in them during that discharge.

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AGGRADATION AND DEGRADATION OF ALLUVIAL SAND DEPOSITS, 1965 TO 1986, COLORADO RIVER, GRAND CANYON NATIONAL PARK, ARIZONA

High discharges in 1983-85 redistributed sand stored in zones of recirculating current in the Colorado River in Grand Canyon National Park. Redistribution resulted in net loss in the number of reattachment deposits in narrow reaches and aggradation of some separation deposits. Separation deposits were more stable than other types of deposits. Alluvial sand deposits that are large enough and of sufficient aerial extent for use as campsites were more stable than smaller lower-elevation deposits. Fluctuating flows between October 1985 and January 1986 caused erosion throughout the Grand Canyon, including erosion of some deposits created by the high flows of 1983-85.

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INTRODUCTION

Alluvial sand deposits along the Colorado River in Grand Canyon National Park (Figure 1) are used as campsites and are substrate for riparian vegetation. The purposes of this report are to (1) present a classification of alluvial sand deposits in the Colorado River, (2) describe major characteristics of the deposits, and (3) describe changes in these deposits that have occurred since 1965, especially changes that occurred from 1973 through January 1986.

Previous studies on the effects of operations of Glen Canyon Dam on alluvial sand deposits along the Colorado River yielded conflicting results. Howard and Dolan (1981) found that alluvial sand deposits along the Colorado River throughout the Grand Canyon had achieved stable profiles by the late 1970s. Brian and Thomas (1984) concluded that high discharges in 1983 had caused degradation in sand deposits used as campsites within 173 river miles downstream from Lees Ferry. Beus et al. (1985) concluded that the high discharges of 1983 resulted in aggradation of the same type of sand deposits studied by Brian and Thomas. Beus et al. (1985) based their conclusions on repeated surveys of 19 alluvial sand deposits, and Brian and Thomas (1984) based their conclusions on comparison of inventories of all sand deposits used as campsites.

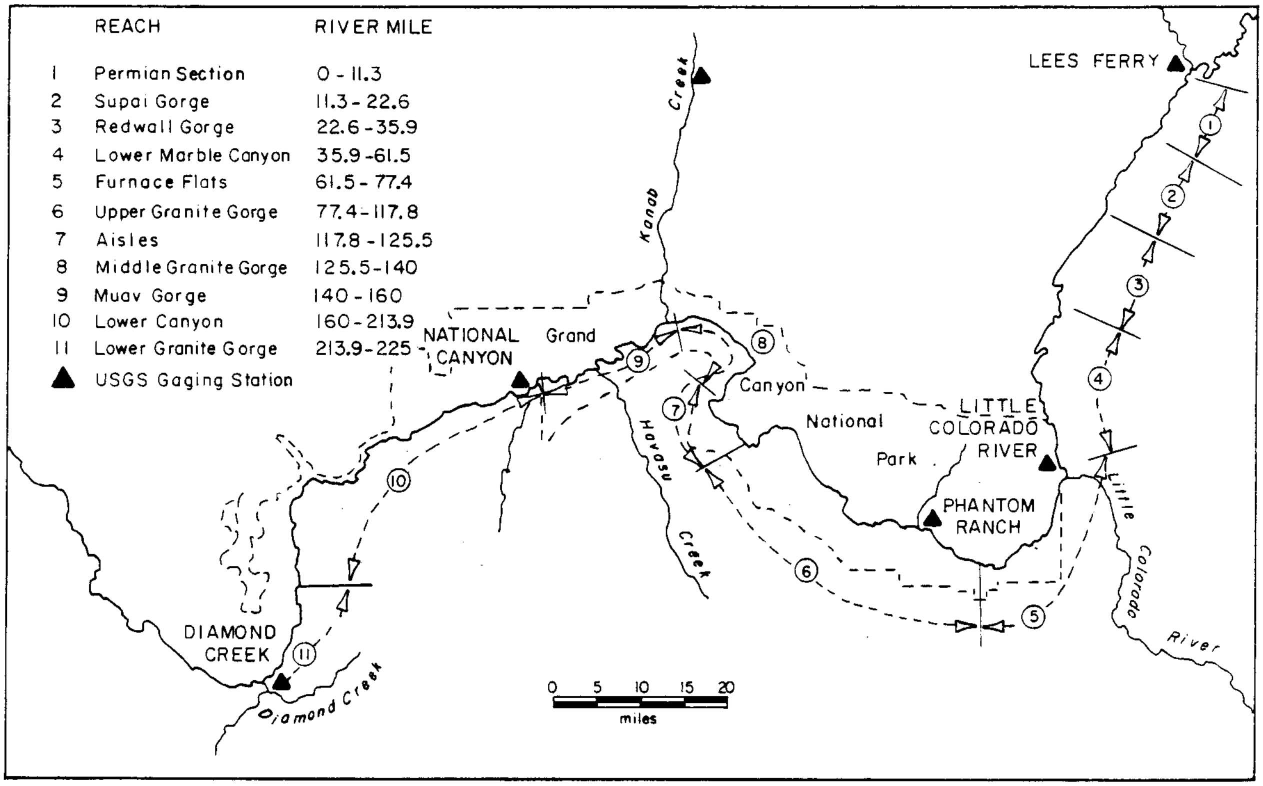
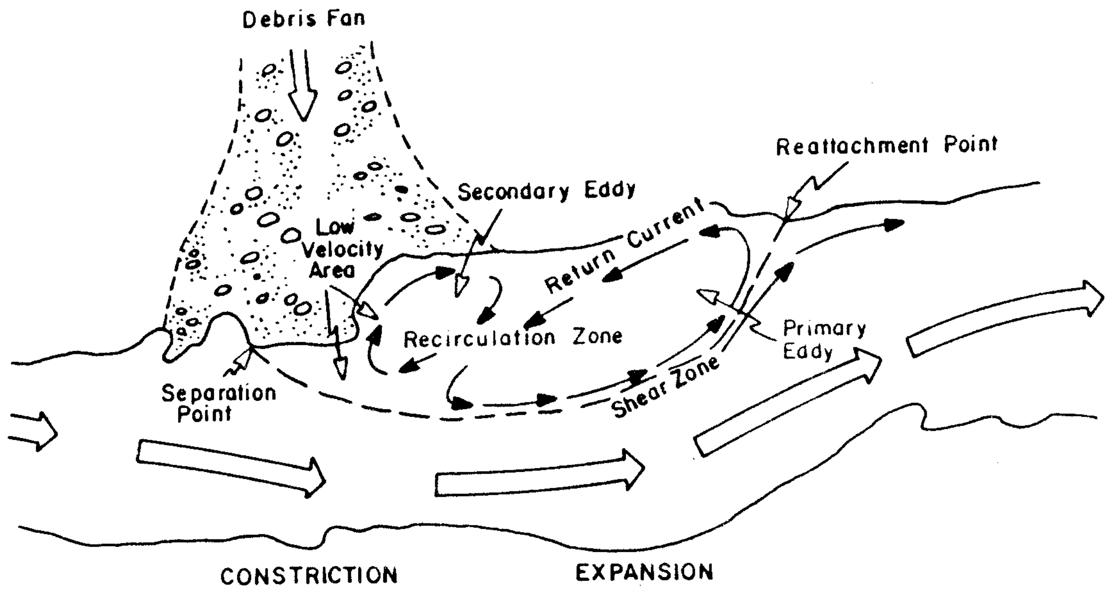


Figure 1. Map of the Colorado River through Grand Canyon National Park and reaches within the study area.

For most of its course through Grand Canyon National Park, the width of the Colorado River is constrained by bedrock and large talus blocks. Debris fans at the mouths of steep ephemeral tributaries partially block the river's course and form riffles or rapids. Notable geomorphic features of the channel in the vicinity of debris fans are (1) the channel constriction, which is a shallow and narrow channel near the apex of the debris fan; (2) a scour hole immediately downstream from the channel constriction; and (3) an expansion in channel width downstream from the scour hole (Figures 2A and 2B). At a broad range of discharges, large zones of recirculating current exist in the channel expansion. The largest and most numerous alluvial sand deposits along the Colorado River are associated with these zones of recirculating current.

Downstream from most constrictions, recirculation zones exist at discharges that range from at least 4,000 to 45,000 cubic feet per second (cfs). At most sites, recirculation zones increase in length with increasing discharges up to at least 45,000 cfs. Lengthening of



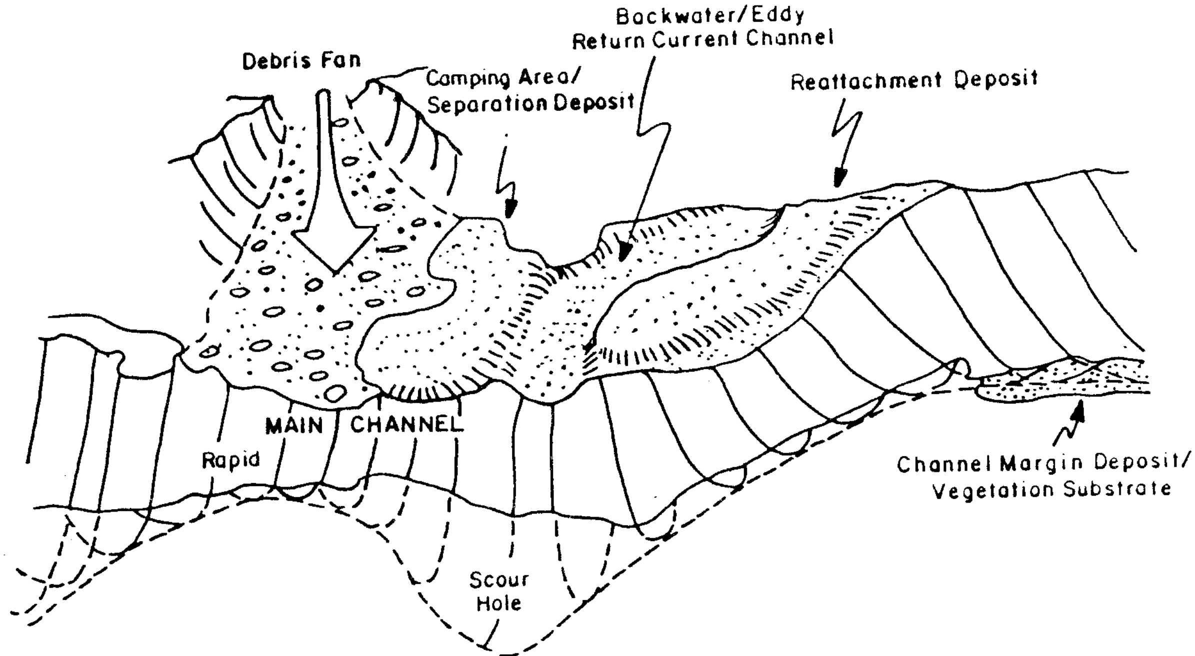


Figure 2. Flow patterns and configuration of bed deposits in a typical recirculation zone. A. Flow patterns. B. Configuration of bed deposits.

recirculation zones usually occurs by upstream migration of the separation point, which is the point at which downstream-directed flow becomes detached from the channel banks. Lengthening also occurs by downstream migration of the reattachment point, which is the point where downstream-directed flow is reattached to the channel banks.

Flow patterns are similar in recirculation zones throughout the Grand Canyon, and specific parts of recirculation zones can be distinguished. Recirculation zones are composed of one or more eddies. All recirculation zones have a primary eddy. They may also have a secondary eddy located upstream from the primary eddy (Figure 2A). That part of the primary eddy where direction of flow is opposite the main downstream current is referred to as the primary-eddy return current. Other parts of recirculation zones are not organized into a rotation and are referred to as low-velocity areas.

Because channel characteristics of the Colorado River vary with the types of bedrock that are exposed at river level, reaches of the river were defined on the basis of average channel top width, average channel shape, reach slope, and relation to major tributaries. Eleven reaches of the Colorado River were defined (Table 1). The narrowest reaches are Upper Granite Gorge, Supai Gorge, and Muav Gorge. The widest reaches are Lower Marble Canyon, Furnace Flats, and the Lower Canyon (Figure 1).

METHODS

Data collected for this study included measurements of flow velocity, scour-and-fill of sand deposits, topographic and bathymetric surveys, mapping of surface-flow patterns, water-surface slope surveys, sedimentological analysis, and replication of photographs. We selected 41 study sites representative of different types of alluvial sand deposits used as campsites. We then developed a classification system of alluvial sand deposits on the basis of morphometric characteristics and the location of these deposits in relation to parts of recirculation zones. Earlier data such as aerial photography and topographic surveys were studied as well.

Two analyses of historical changes between 1973-84 were done: (1) an analysis of change in alluvial deposits in all recirculation zones and (2) an analysis of change

Table 1. Characteristics of the reaches within the study area.

Reach, in miles*	Reach name and number	Average ratio of top width to mean depth**	Average channel width, in feet**	Width character	Channel slope***	Average unit of stream power, in pounds per foot+	Percentage of bed composed of bedrock and boulders++
0-11.3	Permian Section (1)	11.7	280	Wide	0.00099	5.3	42
11.3-22.6	Supai Gorge (2)	7.7	210	Narrow	.0014	10.2	81
22.6-35.9	Redwall Gorge (3)	9.0	220	Narrow	.0015	10.2	72
35.9-61.5	Lower Marble Canyon (4)	19.1	350	Wide	.0010	4.3	36
61.5-77.4	Furnace Flats (5)	26.6	390	Wide	.0021	8.0	30
77.4-117.8	Upper Granite Gorge (6)	7.0	190	Narrow	.0023	17.6	62
117.8-125.5	Aisles (7)	11.0	230	Narrow	.0017	10.9	48
125.6-139.9	Middle Granite Gorge (8)	8.2	210	Narrow	.0020	14.2	68
140-159.9	Muav Gorge (9)	7.9	180	Narrow	.0012	9.9	78
160-213.8	Lower Canyon (10)	16.1	310	Wide	.0013	6.2	32
213.9-225	Lower Granite Gorge (11)	8.1	240	Narrow	.0016	10.2	58

* See Figure 1.

** Average of cross section data at approximately 1-mile intervals at 24,000 cfs (Randle and Pemberton 1987).

*** Based on predicted water-surface elevations at 24,000 cfs (Randle and Pemberton 1987).

\+ Unit stream power is calculated as equal to the following:
(Specific weight of water) (24,000 cfs) (slope of reach)/(average channel width).

++ From channel-bed material maps (Wilson 1987).

in those recirculation zones with deposits designated as campsites by Brian and Thomas (1984). The first analysis was done for 399 recirculation zones between Lees Ferry and River Mile (RM) 117.8. We noted the presence or absence of deposits in each zone, but did not measure deposits because in some reaches stage (river surface level) differed significantly in the 1973 and 1984 photographs.

The second analysis was done for the appropriate recirculation zones between Lees Ferry and RM 35.9 and between RM 122 and RM 160. This analysis, involving about 45 percent of the total number of recirculation zones, included planimetering exposed areas of sand in reaches where stages were similar in 1973 and 1984. The results of the second analysis reflect changes in area of sand exposed at low discharge in those recirculation zones with campsites--the ones of most concern to white-water boaters.

RESULTS

CHARACTERISTICS AND CLASSIFICATION OF ALLUVIAL SAND DEPOSITS. Sand is stored primarily in main channel pools and in recirculation zones. Sand stored in recirculation zones generally is very well sorted and fine to very fine grained in size, whereas sand stored in channel pools generally is medium in grain size.

The pattern of sand deposition in recirculation zones is remarkably consistent throughout the Grand Canyon. Two types of sand deposits within recirculation zones--separation deposits and reattachment deposits--are highest in elevation and are used most by white-water boaters as campsites (Figure 2B). Separation deposits mantle the downstream part of tributary debris fans near the separation point. Reattachment deposits are located at the downstream end of recirculation zones, project upstream into the center of the zones, and are near the reattachment point.

Alluvial sand deposits also may be immediately upstream from constrictions. This type of deposit is referred to as an upper-pool deposit. Deposits whose origin could not be determined on the basis of planimetric shape or location are referred to as channel-margin deposits. Separation and reattachment deposits are not located in every recirculation zone. Where they do occur, however, the location and form in relation to debris fans is consistent from site to site.

Separation deposits form in low-velocity areas and in secondary eddies upstream from the primary-eddy return current. The formation of a bar within a secondary eddy and the upstream migration of this bar onto the debris fan was documented at some sites during high flows in May and June 1985. This process may be responsible for the formation of many separation deposits. Large parts of many separation deposits form at discharges in excess of 30,000 cfs.

Reattachment deposits occur at the downstream end of many recirculation zones and project upstream as spits, filling the zones to a varying extent. A slipface typically exists along the bank side of the spit. Sand is transported across the top of the bar, cascades down the slipface, and is swept upstream by the primary-eddy return current. Sand transported upstream by the return current may be delivered to the main current or be recycled within the recirculation zone. Substantial reworking of reattachment deposits may occur at high discharges. Reworking of these deposits is likely to occur at lower discharges than those needed to rework separation deposits.

DISTRIBUTION OF DEPOSITS. The number of campsites in narrow reaches is limited, with some reaches averaging less than 1 per mile. Alluvial deposits large enough for use as campsites are most numerous in Lower Marble Canyon, Furnace Flats, Aisles, Middle Granite Gorge, and Lower Canyon. The channel in most of these reaches is wide, and the size of alluvial sand deposits is greatest in wide reaches. For example, at a discharge of 5,600 cfs in October 1984, average campsite size was 60,000 square feet in Lower Marble Canyon but was only 8,200 square feet in the narrower Muav Gorge. The increase in number and size of campsites in wide reaches is related to increase in number and size of reattachment and channel-margin deposits. At a discharge of 5,600 cfs in October 1984, channel-margin deposits had an average size of 73,000 square feet in Lower Marble Canyon but had an average size of only 7,500 square feet in Muav Gorge. Reattachment deposits large enough to be used as campsites are numerous only in parts of Lower Marble Canyon, Aisles, and Lower Canyon. The size of separation deposits is greatest in wide reaches; the number of deposits, however, does not vary with width. Local topography of debris fans is the most important determinant in the occurrence of separation deposits.

CHANGES IN ALLUVIAL DEPOSITS, 1973-84. Between June 1973 and May 1983, discharge typically fluctuated on a daily basis in response to hydroelectric generation requirements at Glen Canyon Dam. In contrast, discharge was much higher and steadier between June 1983 and October 1984. Peak discharge at Lees Ferry reached 97,300 cfs in June 1983 and 58,200 cfs in August 1984. Discharge did not vary in relation to hydroelectric power production. Between October 21 and 23, 1984, flow decreased to about 5,600 cfs, and aerial photographs of the river corridor were taken.

Changes in the area of exposed sand deposits between 1973-84 were measured in order to evaluate the effects of high discharges in 1983 and 1984. It was assumed that changes that occurred between 1973-84 were due primarily to high discharges in 1983 and 1984 because (1) peak discharges were much higher and of longer duration than during any other part of the 1973-84 period, (2) Beus et al. (1985) showed that alluvial sand deposits did not change significantly between 1975-80, and (3) Beus et al. (1985) showed that alluvial deposits changed significantly because of the high flows of 1983 and 1984. In 1980, discharge at Lees Ferry exceeded 30,000 cfs for nine days. The effect of these flows is uncertain. In 1983 and 1984, discharge exceeded 30,000 cfs for 149 days and exceeded 40,000 cfs for 120 days.

On the basis of the inventory of separation and reattachment deposits in all recirculation zones between Lees Ferry and RM 118, we concluded sand was eroded from recirculation zones in narrow reaches, regardless of distance downstream from Glen Canyon Dam. The greatest decrease took place in Upper Granite Gorge, the narrowest and steepest reach evaluated (Table 1). The number of recirculation zones with separation or reattachment deposits in wide reaches increased between 1973-84, indicating that the volume of sand stored in recirculation zones in wide reaches may have increased.

Measurements of change in area of major alluvial sand deposits in reaches where discharges in 1973 and 1984 were similar indicate that the largest and highest alluvial sand deposits are less susceptible to change than are other alluvial deposits. Summation by reaches of all increases and decreases in area indicates that no significant change in total area of major alluvial sand deposits occurred in any reach, except between Lees Ferry and RM 11.3. All change measured in that reach was due to erosion of one point-bar deposit. Summation of net-area change of separation and reattachment deposits by reach indicates that significant decreases occurred in separation deposits in Muav Gorge and in reattachment deposits in Supai Gorge.

The general susceptibility to change of separation and reattachment deposits was also evaluated. Summation of the number of major separation and reattachment deposits that increased or decreased in area showed that in most reaches reattachment deposits are more susceptible to change than are separation deposits. Of the total number of separation deposits evaluated, about 40 percent did not change in area. Of the total number of reattachment deposits evaluated, about 20 percent did not change in area. The inventory of alluvial sand deposits in all recirculation zones also indicated that reattachment deposits had more changes than separation deposits. In all but one reach, the number of reattachment deposits that increased or decreased in occurrence exceeded the number of separation deposits that increased or decreased in occurrence. These results confirmed an analysis of change in size of all alluvial deposits between Lees Ferry and RM 20 (Schmidt 1986), which showed that separation deposits are more stable than reattachment deposits. Comparison of the area of sand exposed at about 25,000 cfs in 1973 and 1984 indicates that vertical aggradation of separation and channel-margin deposits occurred at many sites and is consistent with that determined by Beus et al. (1985).

CHANGES IN ALLUVIAL DEPOSITS RESULTING FROM HIGH FLOWS IN 1985. Limited data are available concerning changes. At each of four separation deposits that were surveyed, aggradation occurred in small areas associated with low-velocity areas upstream from the primary-eddy return current. Measurements at Eighteen Mile Wash indicate that scour may precede the period of fill. Each of three reattachment deposits surveyed degraded because of these high flows.

CHANGES IN ALLUVIAL DEPOSITS RESULTING FROM FLUCTUATING FLOW IN 1985. Although parts of some alluvial deposits aggraded, all deposits experienced net degradation. Of 41 profile lines at 13 separation-deposit study sites, about one-fourth of the profiles showed aggradation, and about three-fourths of the profiles showed degradation. The mean net change of separation deposits was -0.65 ft. Erosion in excess of 1 ft was measured at profiles at six sites--five of which are located in narrow reaches. At the end of the period of fluctuating flow, cutbanks existed at many sites, which indicated that profiles were not yet stable.

Comparison of topographic changes with local water slope and nearbank velocity indicate that neither steep water slope nor high nearbank velocity necessarily causes the greatest erosion. The fact that five of six sites with greatest erosion are located in the narrowest reaches indicates that the range of stage change is the most important factor in determining locations of degradation.

Sites where erosion was significant during fluctuating flow are also sites where aggradation was significant following high flows in 1983 and 1984. The only sites where this pattern was not obvious were in narrow reaches where high separation deposits were armored from further erosion by exposure of underlying debris fan deposits near the edge of the water. Fluctuating flows, therefore, significantly eroded those sites where aggradation from high flows had occurred.

The upper surface of most surveyed reattachment deposits degraded during fluctuating flow. Bathymetric surveys of one site indicate that fluctuating flows tend to smooth out the distinctive topography of reattachment deposits. For example, sand removed from the crest of reattachment deposits may be deposited on the slope extending from the crest of the deposit to the channel thalweg.

Bathymetric surveys at three sites show that net volume changes can occur in recirculation zones at a broad range of discharges. At each of these sites, data indicate that large volumes of sand may be exchanged between recirculation zones and the main channel even at moderate or fluctuating discharges.

DISCUSSION

Separation deposits are more stable than reattachment deposits. The greater stability of separation deposits can be related to the different environments of deposition of separation and reattachment deposits. Separation deposits form in lower-velocity areas of recirculation zones. At sufficiently high discharge, both types of deposits may be reworked; however, the threshold for such reworking is probably higher for separation deposits.

Fluctuating flows during the period October 1985 to January 1986 caused significant erosion throughout the Colorado River in Grand Canyon. Such erosion indicates that alluvial sand deposits formed or reworked by steady high flows such as occurred between June 1983 and September 1985 are unstable when initially exposed to fluctuating flows. Although erosion was significant throughout the Grand Canyon with the onset of fluctuating flows, results of topographic surveys in the late 1970s indicate that equilibrium profiles may develop after a number of years of fluctuating flows.

Generally high rates of degradation in alluvial sand deposits in narrow reaches indicates that campsites in these reaches may decrease over time. The number of campsites in these reaches are already limited. If loss of sand deposits continues, the disparity in campsite availability between narrow and wide reaches may be accentuated over time.

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SANDY BEACH AREA SURVEY ALONG THE COLORADO RIVER IN THE GRAND CANYON NATIONAL PARK

Beach profile elevation information was gathered for 24 sites and maps drawn for 23 Colorado River beaches, showing prominent vegetation, use areas, rocks, and sandy areas. 1985 profile changes for six beaches surveyed in 1974 and 1980 are discussed.

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INTRODUCTION

The fate of beaches (sand bars) along the Colorado River in Grand Canyon National Park is of major concern. Beaches provide habitat for flora, fauna, and river recreationists. Prior to construction of Glen Canyon Dam in 1963, the sandy beaches were dynamic, alternately degraded and aggraded by wide ranges in flows and sediment loads. Since 1963, the controlled releases from Glen Canyon Dam have been nearly sediment free. The average annual maximum flow has been reduced from approximately 87,000 cubic feet per second (cfs) to 28,000 cfs, and the median sediment concentration has been reduced from 1,500 parts/million to 7 parts/million (Turner and Karpiscak 1980). The future of river terraces and beaches is uncertain. It has been hypothesized that beaches below Glen Canyon Dam will vanish in 200 years or more (Laursen et al. 1976).

The first quantitative study of the rate and pattern of beach profile changes in the Grand Canyon was initiated by Alan Howard (1975) of the University of Virginia. In 1974 and 1975, Howard established 20 beach study sites consisting of 38 profile lines. Each site had one to three profile lines oriented roughly perpendicular to the river. In the fall of 1980, the U.S. Bureau of Reclamation's Durango Projects Office (DPO) resurveyed the 20 Howard beach site profile lines and established 4 new beach study sites. The sites have been resurveyed over the years by others (Dolan 1981, Beus et al. 1982, 1984, 1985).

The original objective of this study was to measure the rate of erosion of selected sandy beaches along the Colorado River. However, in the summer of 1983, Glen Canyon Dam released flows in excess of 90,000 cfs. The high releases altered the sandy beaches by eroding, eliminating, or aggrading existing beaches, or by creating new ones (Brian and Thomas 1984). Due to the changes in beach profiles after the 1983 high flows, detailed mapping was needed to establish a data base for monitoring future beach changes.

In May and September 1985, 24 sites (Table 1) were surveyed in this study. Of the 24 sites, 16 were newly established, 4 had been surveyed earlier by Howard in 1974 and 1975, and 4 by the DPO in 1980. The sites were selected from a list of the top ten potential sites suggested by the Glen Canyon Environmental

Table 1. List of the 24 sites surveyed during May and September 1985, by name and river mile (Belknap 1969). "L" refers to left and "R" to right side of the river looking downstream.

Beach Name	River Mile (RM)	Reach
Soap Creek	11.3R	1
20 Mile Beach+	20.0L	1
North Canyon	20.5R	1
Nautiloid Canyon*+	34.7L	1
Tatahatso	37.2L	1
Saddle Canyon+	47.1R	1
Lower Saddle Camp	47.2R	1
Lower Nankoweap*+	53.0R	1
Kwagunt	56.4R	1
Above Little Colorado	61.1R	1
Below Little Colorado*+	61.8R	2
Upper Unkar	72.1R	2
Cremation	85.6L	2
Granite Rapid	93.4L	3
Bass Camp	108.3R	3
120 Mile Camp	119.8L	3
Enfilade	123.5L	3
Deer Creek Falls+	136.2L	3
Last Chance	155.7R	3
National Canyon	166.5L	4
Fern Glen	168.0R	4
Lower Lava Falls*+	180.9R	4
Upper Two Rock Camp+	220.0R	4
Middle Two Rock Camp	220.1R	4

* indicates the sites established by Howard in 1974-1975.

\+ indicates sites surveyed by Durango Projects Office in 1980.

Studies Biology, Recreation, and Sediment/Hydrology Subteams. Ten sites were surveyed in the 60-mile reach from Lees Ferry to the Little Colorado River, three in the 26-mile reach from the Little Colorado River to Bright Angel Creek, six in the 81-mile reach from Bright Angel Creek to National Canyon, and five in the 58-mile reach from National Canyon to Diamond Creek.

METHODS

For this study, DPO used a survey technique combining the profile line method used by the Howard surveys and the standard transit-stadia topography survey method. A baseline running parallel to the river with profile lines covering the beach area were surveyed for all sites. For the previously established sites, attempts were made to locate and use any reference points, baselines, and profile lines from past surveys. A detailed beach survey was obtained by spacing the profile lines 25 to 50 ft apart and perpendicular to the baseline. The spacing varied with the amount of terrain change along the baseline, The length of the baseline, and the time available for the survey. The transit-stadia topography survey method was used to obtain data in areas the profile lines did not cover.

At each beach, the baseline and reference points were established in stable areas above the effects of the normal fluctuating river stage (approximately 35,000 cfs). The majority of the reference points were located on the baseline and were set in stable boulders and rock outcrops. The datum elevation, usually a reference point, was assumed to be 100.0 ft unless a known elevation point was located. Points on the profile lines were selected to best describe the beach area with the fewest possible shots. These points were located at the top and toe of slopes, break in slope, and at places of distinctive change, such as at the edge of sand, rock, vegetation, water, or a camping area. For each reference point, the elevation, distance, and a brief description were recorded in the survey notes, and the elevation and location were recorded on a map. Information needed to recreate the baseline and profile line alignments was documented with written descriptions, maps, and photographs.

Plane table maps were sketched during the field survey showing the baselines, benchmarks, vegetation, rocks, and sand clearings. The maps were oriented to true north using a Brunton handheld compass. The scale depended on the length and width of the beach area.

The measured field elevations were placed on the map along with a general description of the area and other pertinent information. Contour maps (example at Figure 1) were then developed for 20 of the 24 beach areas using the field data and a computer contour plotting program called "Surface II Graphics System" (Sampson 1975).

Problems can arise when survey lines are resurveyed, especially by a different crew. If the resurvey crew does not have clear photos, maps, and notes of the original survey, relocating the profile lines can be difficult, if not impossible. Errors may also increase over time. During this study, a few of the reference points could not be relocated because of tributary flash floods, site alteration by people, or vegetative growth. To avoid future problems, the survey crew tried to select points in stable areas and document them with photographs and survey data.

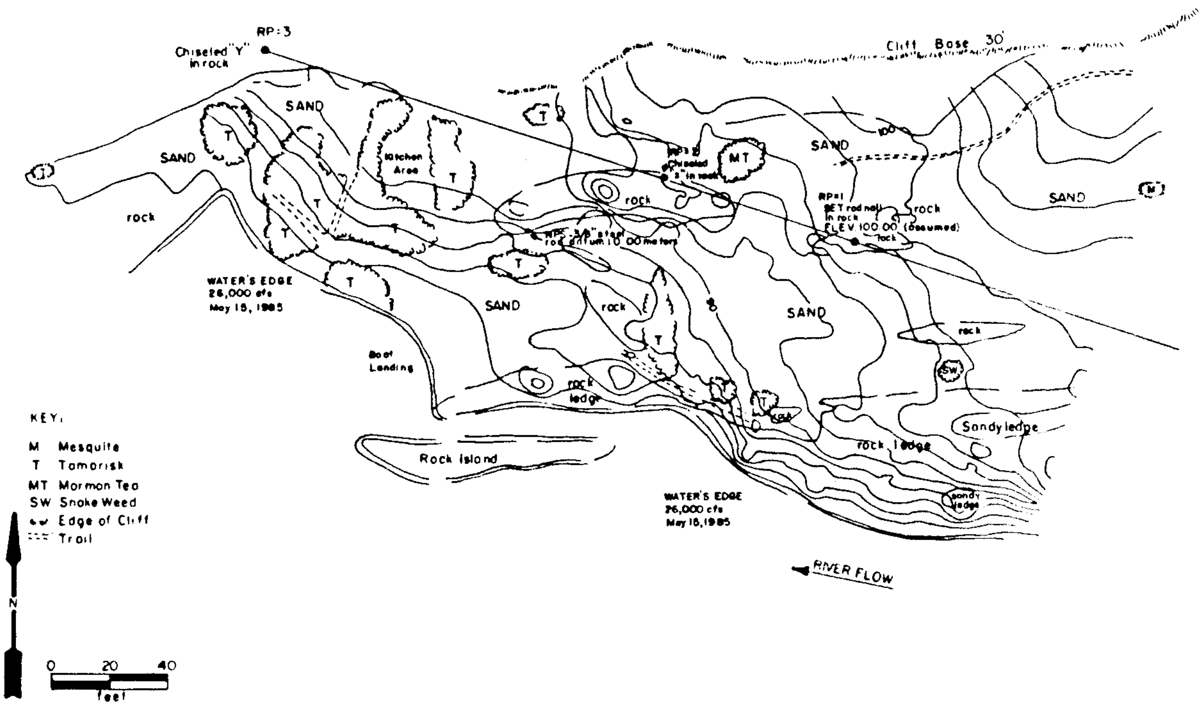

Figure 1. Example of a beach site (Lower Bass, RM 108.3R)

The field survey data for this study is on file at Division of Resources Management and Planning, Grand Canyon National Park, Arizona; the Bureau of Reclamation, Upper Colorado Regional Office, Salt Lake City, Utah; and the Durango Projects Office, Durango, Colorado. It is suggested that beaches be resurveyed every one to five years. Resurveyors should create a new map using the original datum and baseline, with profile lines extending to the water surface or beyond.

RESULTS

BEACH PROFILES. Profile lines at two of the eight previously established sites (Nautiloid Canyon and Lower Lava Falls) could not be relocated. Thus only six of the eight original survey sites were compared in this study. A total of ten profile lines at these six sites were resurveyed and compared with original profile line data. The data were then graphically plotted to illustrate the changes between surveys (an example, Nankoweap [RM 53.0R] is shown in Figure 2). The graphs were plotted with the baseline station being zero and the river shoreline to the right. The plotted elevations were relative to the 100-ft datum assumed in the field. To show the detail of change, the vertical elevation scale was expanded. The following is a discussion of each of the eight survey sites which had previously been surveyed by the Howard and DPO studies. The beaches are discussed in order of their occurrence below Glen Canyon Dam.

The 20 Mile Beach baseline (established March 1980 by DPO) was relocated except for one reference point. Two profile lines were compared: line 10+50 (located in a rocky zone near a river recreationist high-use area) and line 11+00 (located in a sandy high-use area). The first profile line degraded -2 ft along a majority of the line. The second profile line aggraded +1 ft in the upper area and degraded - 0.5 ft along the lower reach. The gain and loss of beach material is hypothesized to be a result of the 1983 high flows which submerged the upper portion of the beach, normally above post-dam river flows.

Nautiloid Canyon base survey station #1 (established June 1974 by the Howard survey and resurveyed October 1980 by DPO) was not relocated because a flash flood down Nautiloid Canyon had altered the site. Base station #2 was located under 1.5 ft of sand--probably deposited during the 1983 flow. A comparison with the two previous surveys could not be made, however,

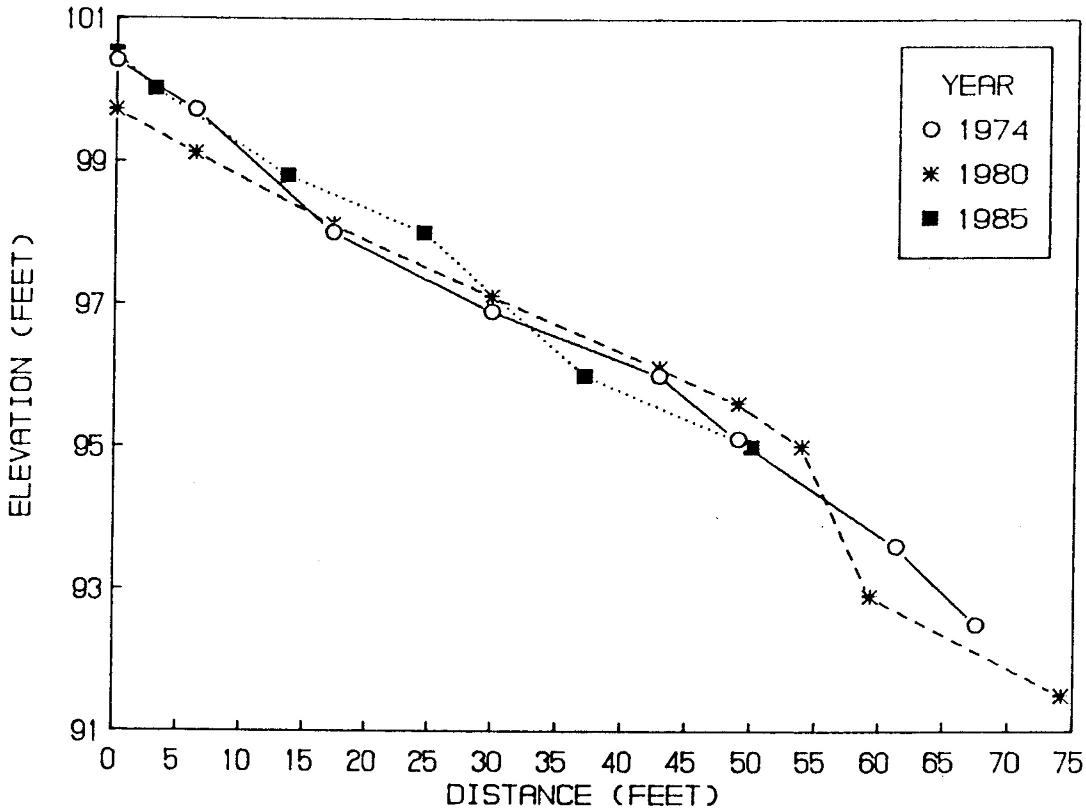

Figure 2. Plotted profile of Nankoweap Beach (RM 53.0R)

because base station #1 was the datum point and the other base stations had no known elevations.

The Saddle Canyon profile (established October 1980 by DPO) was used as the baseline for the topographic map. comparison of the two surveys showed little change for the past five years.

Two of the Lower Nankoweap baseline stations (established June 1974 by the Howard survey and resurveyed in 1980 by DPO) were not relocated, but the survey crew recreated the original baseline using available data. A comparison was made with the original three profile lines by using the topographic contour map. Profile lines CS1 and CS2 (located within the high-use area) showed a slight change over the years. Line CS3 (located in a very high-use area) showed a -1.5 ft loss of material.

The Below Little Colorado site (established July 1975 by the Howard survey and resurveyed October 1980 by DPO) was not mapped due to limited field time. The baseline and profile line were used for comparisons and showed an aggradation of +2 ft at the baseline and profile line intersection, but a loss of material as the profile line extends toward the river.

The Deer Creek site (established October 1980 by DPO) downstream reference point was not relocated. However, the baseline and profile lines were relocated using the upstream reference point and the known azimuth of the two lines. A comparison of the two surveys showed little change in five years.

Lower Lava Falls profile lines (established June 1974 by the Howard survey and resurveyed October 1980 by DPO) could not be resurveyed. High flows of 45,000 cfs inundated the site during the May 1985 field trip.
The Two Rock Camp profile lines (established November 1980 by DPO) were compared to the contour map developed during this study. Profile line CS1 degraded a maximum of -2 ft. Profile line CS2 aggraded up to +1 ft on the upper portion of the profile and degraded -1 ft as the profile line extends towards the river. Both profiles are located in high-use areas.

A quantitative comparison (Table 2) of the deposition or erosion occurring along the profile lines at six of the beaches discussed above was made for the upper, middle, and lower portions of each profile. Plotted profiles (see Figure 2 for an example) were used to attain the values. The upper part of the profiles is located farthest away from the water's edge. Caution must be used in interpreting change shown by the profile line comparisons. The values are based on a limited number of profiles and surveyed beaches. They represent only general trends of changes within the surveyed beach areas above the water's edge.

The quantitative general comparison of the profiles at the six beaches indicates a weighted average of +0.5 ft deposition in the upper portion, about -0.5 ft erosion in the middle portion, and about -1.0 ft erosion in the lower portion, with approximately -0.5 ft erosion for the overall profiles. The deposition of about +0.5 ft shown for the upper portion of the surveyed profile lines may be attributed to the high flow event from Glen Canyon Dam in 1983. The erosion in the middle and lower portions of the surveyed profile can be attributed to the high flows in 1983-1984 and to river fluctuations, wind erosion, and recreationist use from 1980 to 1985.

Table 2. Profile line comparisons for six beaches resurveyed by this study. Weighted values for six beaches are rounded to nearest 0.5 ft.

Beach (Survey Dates)	Line	Change in Feet Upper	Middle	Lower	Total
20 Mile	10+50	-1.0	0	-2.0	-2.0
(1980,1985)	11+00	+1.0	0	-0.5	0
	Average	0	0	-1.2	-1.0
Saddle		0	0	0	0
(1980, 1985)					
Lower Nankoweap	CS1	+0.5	-0.5	-	0
(1974, 1980,	CS2	+0.5	+0.5	-	0.5
and 1985)	CS3	-1.5	-1.5	-	-1.5
	Average	-0.5	-0.5	-	-0.5
Below Little Colorado					
(1975, 1980, 1985)		+2.0	-2.0	-	-1.5
Deer Creek					
(1980, 1985)		+1.0	-1.0	-	0
Two Rock Camp	CS1	+1.0	-2.0	-2.0	-1.5
(1980,1985)	CS2	0	+1.5	-1.5	0
	Average	+0.5	-0.2	-1.7	-0.7
Weighted For All Beaches		+0.5	-0.5	-1.0	-0.5

\+ equals deposition

\- equals erosion

BEACH AREA MAPS. Twenty-three beach area elevation maps (21 x 36 in) were developed during this study (Ferrari 1987). A map was not done for the Below Little Colorado site due to limited time available during the field survey. Contour maps were developed for 20 of the 23 beach area map sites (see Figure 1 for an example). Three of the survey sites (20 Mile, Last Chance, and Below Lava Falls) did not have adequate elevation points to create accurate contour maps.

CONCLUSIONS

Ten profile lines at six sites previously surveyed in 1974-1975 and 1980 were resurveyed by this study. Profile lines on a beach give a detailed two-dimensional description of the transect line. However, changes along these profile lines do not always reflect change for the entire beach area. Some of the profile lines were located in areas impacted by side canyon flash floods or recreationists. Thus, conclusions can not be made about the rate of change for the beach by extrapolating exclusively from the data collected at the profile lines. Profile lines for two sites (Nautiloid and Lower Lava Falls) could not be relocated. A general comparison of the profile lines shows no change at two sites (Saddle and Deer Creek) and deposition or erosion of up to 2 ft at the other four.

Beach area maps for 23 sites were developed by this study. No conclusions about the total beach area changes can be made until the sites are resurveyed.

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TRENDS IN SELECTED HYDRAULIC VARIABLES FOR THE COLORADO RIVER AT LEES FERRY AND NEAR GRAND CANYON, ARIZONA, 1922-84

Trends in selected physiographic and hydraulic variables are interpreted from historic stream flow records at two gaging stations: Colorado River At Lees Ferry and Colorado River Near Grand Canyon, Arizona. The relationship between riverbed level, discharge, velocity, and riverbed scour-and-fill are discussed.

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INTRODUCTION

The general objective of the study was to glean factual information about the dynamics of the Colorado River from historical streamflow data for the two gaging stations "Colorado River at Lees Ferry, Arizona" and "Colorado River near Grand Canyon, Arizona." The historical streamflow data for each station were closely examined for information concerned with: (1) changes in the ability of the Colorado River, for a given stage, to transport water and sediment; (2) scour-and-fill in a rapid immediately downstream from each gage site; (3) scour-and-fill in cross sections of the river where discharge measurements are made; and (4) the relationship between regulation of flow and changes found in (1), (2), and (3). The data used in the study are for 1922-84.

The channel of the Colorado River has a pool-and-rapid form through most of the Grand Canyon (Leopold 1969). The rapid section, generally part of an alluvial fan located at the mouth of a tributary stream, is usually composed of gravel, cobbles, and large boulders. A typical rapid is relatively stable, except during floods or debris flows in the tributary stream when fill may occur. The typical pool represents a sediment sink. The bed of the pool has an elastic characteristic--the boundary of alluvial sediments typically scouring as the discharge increases and filling as the discharge decreases.

The two gaging stations, Colorado River At Lees Ferry and Near Grand Canyon, are located in pool sections upstream from rapids. The rapids represent controls (Chow 1959) for the gage sites. The Lees Ferry gage is about 16 miles downstream from Glen Canyon Dam and about 200 ft upstream from the rapid at the mouth of Paria River. The site known as Near Grand Canyon is about 101 miles downstream from Glen Canyon Dam and about 0.4 mile upstream from the rapid at the mouth of Bright Angel Creek. The drainage areas are approximately 111,800 square miles for the basin above the Lees Ferry gage and about 141,600 square miles for the basin above the Grand Canyon site. The flow of the Colorado River has been regulated at Glen Canyon Dam since 1963. Flow from streams tributary to the Colorado River below Glen Canyon Dam is unregulated.

METHODS

Trend analyses were performed in which curves were developed to show temporal changes in:

(1) riverbed level,
(2) discharge-to-velocity relationships, and
(3) discharge-to-stage relationships.

Five variables were used in the analyses: water discharge, stage (river surface level), river depth, and time. These data were taken directly from streamflow measurement notes. For each gaging station, about 1,400 sets of data for 1922-84 were available for study.

Significant changes in trends, as indicated by the curves, were correlated as nearly as possible to factors that caused the change. Bed-level values, each of which represents the channel bed at the low point during the time a discharge measurement was made, plotted against time were the basis for curves which show temporal changes in riverbed level.

Shifts, taken as the difference between computed and measured values of velocity or stage, plotted against time were used to investigate temporal changes in the discharge- to-velocity and discharge-to-stage relationships, respectively (Burkham and Guay 1986). The model used to represent the average (1922-84) discharge-to-velocity relationship for each site is $V=A(QM)^B$, in which A is a coefficient, V is mean cross-sectional velocity, QM is measured discharge, and B is an exponent. The model used to represent the average (1922-84) discharge-to-stage relationship for each site is $GH=C(QM)^D+E$, in which GH is gage height or stage of water surface, C is a coefficient, QM is measured discharge, D is an exponent, and E is a parameter. Iteration routines and least-square regression analyses were used to develop estimates for A, B, C, D, and E.

RESULTS AND CONCLUSIONS

The regulation of flow with the construction of Glen Canyon Dam has caused a significant change in the flow pattern at the two gage sites. The pre-dam discharge at the sites usually fluctuated greatly during a year, averaging about 17,900 cubic feet per second (cfs) in 1912-62 at the Lees Ferry site and about 16,900 cfs in 1922-62 at the Grand Canyon site (U.S. Geological Survey, issued annually). During some years in 1922-62, the discharge at the two sites ranged from more than 200,000 cfs to less than 1,000 cfs. Relatively high discharges usually came in winter (November through June). Typically, the pre-dam concentration of suspended sediment was significantly greater in summer (July through October) than in winter (U.S. Geological Survey, issued annually).

In the 20 years following construction of the dam (1964-84), discharge at the two sites fluctuated often, but through a relatively narrow range compared to that of pre-dam years. Discharge in the period 1965-82 averaged about 12,200 cfs at the Lees Ferry site and about 12,700 cfs at the Grand Canyon site (U.S. Geological Survey, issued annually). The discharge ranged from about 5,000 to 33,000 cfs most of the time in 1965-82. The post-dam maximum discharge (approximately 97,000 cfs on June 23, 1983) was equalled or exceeded almost annually prior to the construction of Glen Canyon Dam. The concentration of suspended sediment in flow released at the dam in 1965-82 was insignificant.

COLORADO RIVER AT LEES FERRY, ARIZONA.

RIVERBED LEVEL. In 1922-62, before construction of the dam, the riverbed at the gage site (composed mainly of sand and gravel) typically scoured as streamflow velocity progressively increased above a critical value (5.0 ft/s) and filled as the velocity returned to the critical value. The discharge needed to produce a 5.0 ft/s velocity when the bed was at a high level was about 18,000 cfs. During some winter floods, the alluvial deposit was scoured more than 20 ft. However, the riverbed at the low point in the measurement section was at a pool-full (high) level (about 1.0 to -2.0 ft elevation [local datum]) most of the time in 1922-40 because the streamflow velocity was usually less than that required to start and sustain erosion.

Each year, prior to about 1940, the riverbed at the low point returned to a pool-full level soon after the cessation of high discharges. In 1940-1962, however, after high discharges, he riverbed at the low point returned to a level slightly lower than that for the preceding year. The result was a fluctuating decline in the level of the riverbed in 1940-62.

In post-dam 1965, when the regulated discharge ranged from 40,000 to 60,000 cfs for more than 40 days, the alluvial sediments at the low point in the measurement section scoured about 27 ft. The amount of fill in 1965 and 1966, after the cessation of high discharges, was only about 12 ft. During 1967-82, years in which the regulated flow normally ranged from 5,000 to 33,000 cfs, the low point in the riverbed remained relatively constant at -15 to -16 ft. The dam both prevented the high flows necessary for scouring and trapped the sediment necessary for filling.

As a result of high flows released in 1983, the bed scoured an additional 6.0 to 7.0 ft but filled back to about its former level, -15 to -16 ft, after recession of the high discharge. Most of the net change in the riverbed level over the full study period, 1922-1984, has been a direct result of the regulation of water and sediment at Glen Canyon Dam.

DISCHARGE-TO-VELOCITY RELATIONSHIPS. The mean cross-sectional velocity for a given discharge in the range from 2,500 to 33,000 cfs decreased significantly, about an average 3.5 ft/s, during 1922-84. About one half of the decrease in velocity occurred gradually in 1940-62 and about one half occurred abruptly in 1965. A change in the mean velocity of 3.5 ft/s can cause a change in the ability of the river to move sediment by several hundred percent.

The fluctuating declines in bed level and velocity for a given discharge in 1940-62 probably occurred because of a decline in upstream inflow of sediment which resulted in a reduction in the amount of sediment deposited in the pool. This decline in the sediment supply was probably caused by fluctuations in climate. The elimination of sediment due to Glen Canyon Dam caused the sudden increase in cross-sectional area and abrupt reduction in velocity in 1965.

A progressively larger-size sediment apparently was encountered as the depth of scour increased during high discharges in 1922-62. The size of sediment on the bed at the -14- to -16-foot level in 1967-84 was larger than that on the bed at the 1- to -2-foot level in 1922-62.

From 1967 to 1982, the streamflow velocity did not reach a magnitude that would have caused scour even if the sediment on the bed had been of a pre-dam size. However, with the sediment size encountered at the -15- to -16-foot level in 1967-82, an even greater velocity of about 7.0 ft/s (at a discharge of about 70,000-75,000 cfs) would have been required to start scour of the bed.

DISCHARGE-TO-STAGE RELATIONSHIPS. The scour of the riverbed (in the pool upstream from the Paria rapid) and decreased velocity caused a shift in the discharge-stage relationship at the Lees Ferry site. During 1940-62, a progressively higher water surface stage was required to pass a given discharge; the net shift in the relationship amounted to an average of about +0.10 ft. Another shift amounting to +0.35 ft occurred after the large scour in 1965. Therefore, over the entire study period, 1922-84, the discharge-stage relationship for a given discharge in the range from 2,500 to 33,000 cfs shifted an average +0.45 ft. From 1931 to 1984, the decrease in discharge for a stage of 12 ft amounted to about 6,500 cfs.

The level of the control section, the rapid at the mouth of Paria River, did not change significantly in 1922-84. This indicates that the Colorado River in the vicinity of the gage at Lees Ferry does not represent a degrading stream. However, the rapid is subject to an increase in elevation at any time during a flood in the Paria River.

COLORADO RIVER NEAR GRAND CANYON, ARIZONA.

RIVERBED LEVEL. The riverbed in 1922-62 was at a low-bed level, -11.5 to -13.0 ft (local datum), during high winter discharges and during several summer periods, when the discharge was relatively low. During the remaining time in 1922-62, the riverbed was primarily at a high-bed level, -9.0 to -5.0 ft elevation. The range in bed level was about 8.0 ft, compared to more than 20 ft for the Lees Ferry site.

The level of the riverbed at the Grand Canyon site did not return immediately to its pre-flood level after the cessation of high discharges during several years in 1922-62. This fact indicates that only a very limited supply of sand- and gravel-size sediments was available for deposition in the pool during the recession of some floods. Apparently the riverbed in 1922-62 reached a high-bed level mainly in response to large sediment inflows from local tributaries, primarily the Paria and Little Colorado Rivers. The riverbed scoured to about the -13- ft level during 1965 when the release rate of sediment-free water was in the range from 40,000 to 60,000 cfs.

Starting in 1967 and ending in 1983, the riverbed stayed at the high-bed level. Two factors were involved in keeping the bed at this level: a flood on Bright Angel Creek in 1966 and the regulation of flow at Glen Canyon Dam. The 1966 flood brought large amounts of debris--large boulders, cobbles, gravel--to the mouth of Bright Angel Creek. Much of this debris became lodged on the control (rapid) downstream from the Grand Canyon gage. The elevation of the riverbed at the rapid increased, causing the riverbed at the Grand Canyon gage to rise by about 4.0 ft. Because the regulated flow did not create enough energy to remove it, the debris largely stayed in place on the rapid in 1967-82. However, the riverbed at the rapid scoured some in 1971-73, and the debris on the rapid apparently was slowly being eroded in 1977-82 because the bed level at the gage was gradually being lowered. The 1983 flood in the Colorado River removed the debris from the rapid at the mouth of Bright Angel Creek, and the riverbed at the gage returned to a low-bed level.

DISCHARGE-TO-VELOCITY RELATIONSHIPS. In 1922-62, when the bed was at a high-bed level, a velocity of about 5.5 ft/s (at a discharge of about 20,000 cfs) was required before scour began. However, a discharge of more than 100,000 cfs and velocities of about 10 ft/s would not cause the bed to scour to more than about -14 ft. The bed did not scour below the -14-ft level because the size of sediment in the bed increased and the mean velocity for a given discharge decreased with scour depth. As defined by discharge measurements, the mean velocity was less than 5.5 ft/s for all but five discharges measured in 1967-82.

DISCHARGE-TO-STAGE RELATIONSHIPS. The discharge-stage relationship shifted about +3 to +4 ft as a result of the debris being moved to the Bright Angel rapid during the flood of 1966. During 1971-82, the stage required to produce a given discharge gradually decreased about 2 ft. During the Colorado River flood of 1983, the stage-discharge relationship returned to a state that existed in 1966 before the Bright Angel debris flow. The discharge-stage relationship at the Bright Angel rapid is subject to change during any period of significant flow in Bright Angel Creek.

COLORADO RIVER.

Most of the results and conclusions for the two gage sites are applicable to similar sites at pool-and-rapid reaches along the Colorado River upstream from the Grand Canyon gage. They also may be applicable to similar sites downstream from the Grand Canyon gage.

The 1983 flood caused a significant amount of sand-size sediment to move past the gage at Lees Ferry (U.S. Geological Survey, issued annually). This sediment eroded from the riverbed and banks in the reach from Glen Canyon Dam to Lees Ferry. A limited supply of alluvial sand- and gravel-size sediment is still available in the reach from Glen Canyon Dam to Lees Ferry. Of this supply, the part that will erode probably will be relatively small except during periods when the discharge is greater than 70,000 to 80,000 cfs.

In 1984, tributary streams (mainly the Paria and Little Colorado Rivers) are the primary source of sediments that are/or will be available to maintain beaches along the Colorado River from Lees Ferry to the Grand Canyon site and even further downstream. Sediments presently (1984) in Colorado riverbed pools are probably of secondary, if any, importance.

Given that at some time in the future the riverbed in pools in the reach from Lees Ferry to the Grand Canyon site will be at a high-bed level, further inputs of sediments from tributary streams will be primarily wasted downstream. The regulated streamflow presumably will have the capacity to move the sediment when the riverbed in the pools are at a high level.

The Colorado River in the Grand Canyon, because of the stability of the rapids, does not represent a typical degrading stream which often develops when a dam is constructed. Rapids along the Colorado River in the Grand Canyon are eroding only gradually, if any, during the present regulated-flow regime. The levels (elevations) of the rapids, however, are subject to abrupt increases during periods of debris flow in tributaries.

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SEDIMENT DATA COLLECTION AND ANALYSIS FOR FIVE STATIONS ON THE COLORADO RIVER FROM LEES FERRY TO DIAMOND CREEK

Sediment data were collected at five sampling stations in the 225-mile reach of the Colorado River below Glen Canyon Dam. The data were used to define sand load rating curves, which were developed from computations of sediment transport using the Modified Einstein Method. The sand load rating curves provide a method to compute, for short reaches of river, the volume of sand either deposited or scoured in the main channel of the Colorado River under different flow release patterns at Glen Canyon Dam.

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INTRODUCTION

Sediment transport studies on the Colorado River below Glen Canyon Dam were initiated under the Glen Canyon Environmental Studies (GCES) to evaluate the short- and long-term impacts of sediment movement on recreation, fisheries, vegetation, and beach erosion of the Colorado River through Grand Canyon National Park. The U.S. Geological Survey, under an agreement with the U.S. Bureau of Reclamation, collected the field data, provided laboratory facilities for the bed material analyses, completed discharge measurements with rating curve development, and assisted in developing and analyzing the criteria for the sediment transport computations. The Bureau of Reclamation was responsible for suspended sediment laboratory analyses and for completion of the sediment transport computations described in this report. To provide data for the evaluation, five sediment sampling stations were strategically located on the Colorado River in the Grand Canyon reach of river below Glen Canyon Dam (Figure 1).

METHODS

The sampling program at each of the five stations included collecting data on suspended sediment, bed material, and channel hydraulics for computations of total load. It was recognized that much of the sand-size sediment considered most critical in replenishing the beaches is transported near or on the

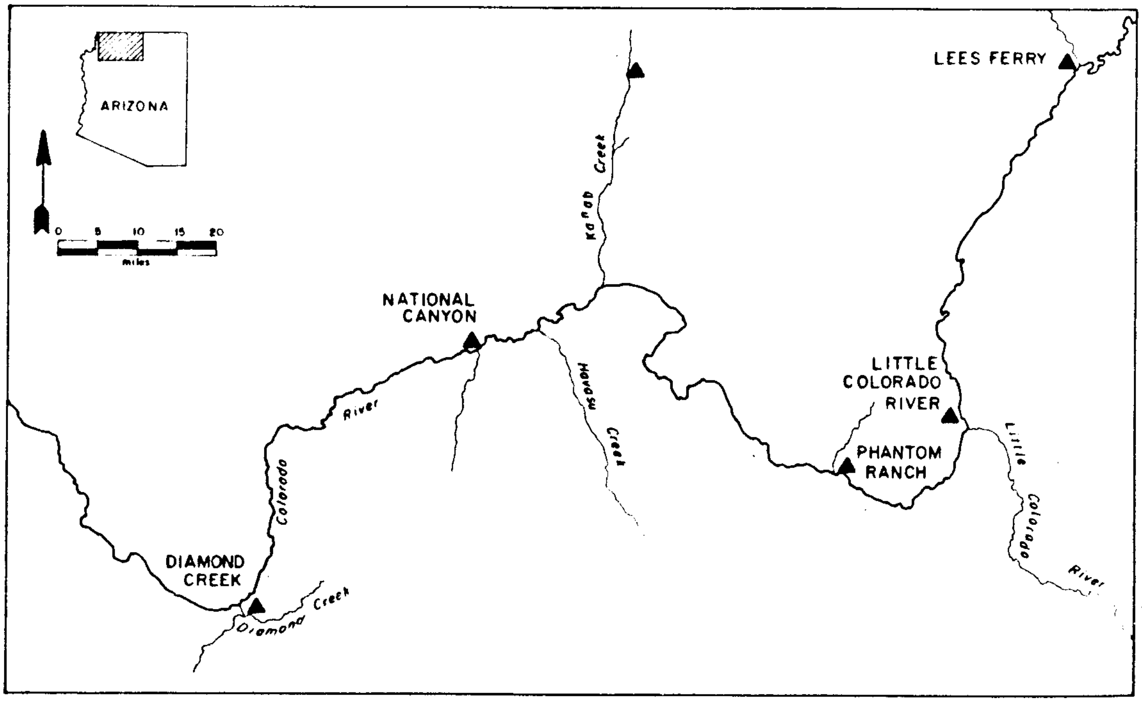

Figure 1. Map of the Colorado River through Grand Canyon National Park with location of the gaging stations.

streambed of the river and cannot be measured under the normal suspended sediment sampling program. The total sand load was derived from the sand load portion of the total sediment load computed by the Modified Einstein Method. Total sand load rating curves (discharge versus sand load) at each of the five sampling locations served two purposes: one, as a control point on the river for verification of the STARS (Sediment Transport and River Simulation) model (Orvis and Randle 1986) developed by the Bureau of Reclamation, and two, to test several of the sediment transport equations to see which is most applicable to the Colorado River.

The sampling period ran in two phases: Phase 1 (June 30, 1983, to December 13, 1983) and Phase 2 (October 1, 1985, to February 2, 1986). Phase 1 was limited to the high discharge range because of the high runoff and operation of the river outlets and spillway at Glen Canyon Dam beginning in June 1983. The high flow releases from Glen Canyon Dam prevailed until October

1985. Sampling under Phase 2 (or the more nearly the normal operation of Glen Canyon Dam Powerplant with fluctuating discharges) ran for about four months beginning on October 1, 1985.

SEDIMENT SAMPLING PROGRAM. The sampling station locations divide the river into four subreaches. This allows for the identification of sediment originating from large tributaries such as the Paria River, Little Colorado River, and Kanab Creek, and permits a better evaluation of sediment transport through the approximately 225 miles of river from Lees Ferry to Diamond Creek.

In addition to sampling at the main river stations, suspended samples were collected in 1983 at gages on the three major tributaries: Paria River, Little Colorado River, and Kanab Creek. These sediment data could be checked against data collected at the same gages in previous years. Sediment load computations for the tributaries and resulting supply to the Colorado River are described in detail in the report by Randle and Pemberton (1987).

Several changes were made in the data collection program for the 1985-86 period, primarily due to the fluctuating flows of Glen Canyon Dam Powerplant releases. In order to adequately sample the peaks, troughs, and rising and falling stages of the flow hydrograph, a schedule was developed for continuous sampling during four-day periods at each station. In the four months from October 5, 1985, to February 2, 1986, each of two crews made four trips down the river collecting eight sets of four-day samples at each sampling site. The only exception to this schedule was at the Lees Ferry location where only about one-third the number of samples were collected (compared to the other stations) because the water there is clear with extremely low sediment concentrations. The example of the sampling schedule at Location 4, Colorado River Near Grand Canyon, shown in Figure 2 is typical.

Sampling equipment used throughout the data collection period included a P-61 sampler for most of the suspended sediment samples and a D-77 for those collected in the early part of 1983. A Price AA Current Meter was used for velocity measurements. A BM-54 was used to collect bed material samples and a Helley-Smith to collect bedload samples.

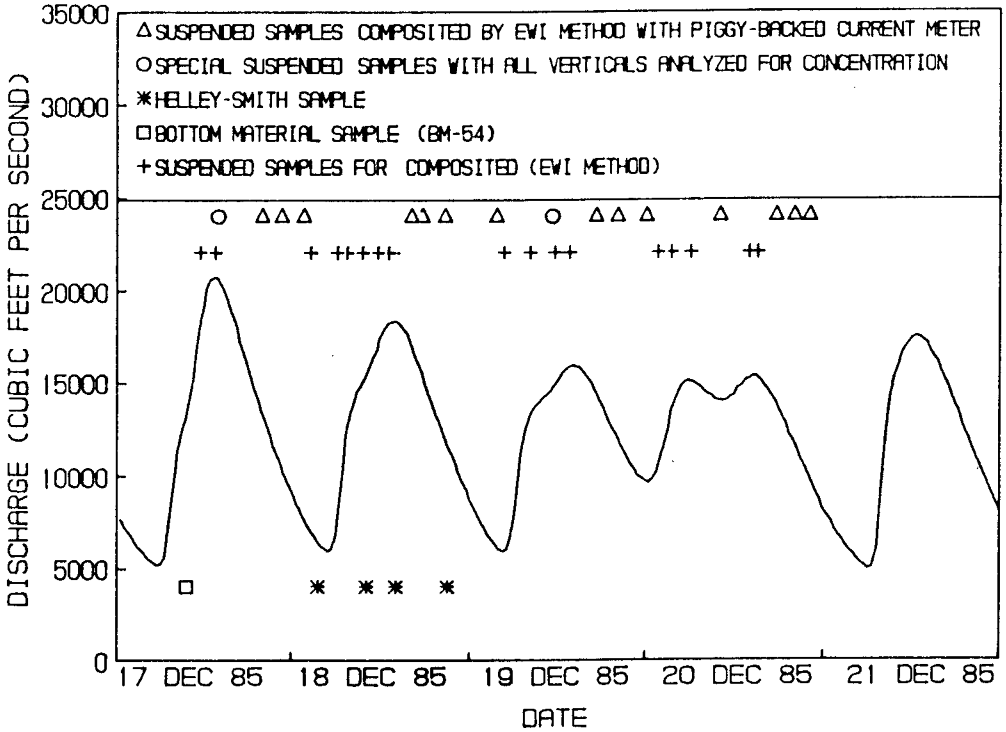

Figure 2. Typical sediment sampling schedule, Colorado River Near Grand Canyon, October 1985 to February 1986.

The time interval between sampling periods permitted an adjustment in the sampling procedure for 1985-86 based on experience gained from the 1983 data analysis. Because of the consistent pattern of streambed material across the cross section in 1983, the bed material samples in 1985-86 were taken less frequently, but at a regular interval. More samples were taken in the cross section to better define the variation across the sampling section. Discharge measurements in 1985-86

were made closer in time to the collecting of suspended sediment samples. For the faster changes in stage and discharge during the rising and falling portions of the flow hydrograph, the current meter was piggy-backed with the sediment sampler for more accurate computed discharges in relation to the actual time of sediment sampling.

BASIC DATA. Suspended sediment EWI (Equal-Width-Increment) samples were analyzed for concentration and size (Guy 1969) in the Bureau of Reclamation's Interregional Soil and Water Laboratory, Denver, Colorado. All other samples, such as bed material and the Helley-Smith samples, were analyzed in the U.S. Geological Survey's Arizona District Laboratory, Tucson, Arizona.

In all laboratory work, the location numbers used to identify the sampling stations were as follows:

Location No.	Station
1	Colorado River At Lees Ferry
2	Paria River At Lees Ferry
3	Colorado River Above Little Colorado River
4	Colorado River Near Grand Canyon
5	Colorado River Above National Canyon
6	Colorado River Above Diamond Creek
7	Little Colorado River At Cameron
8	Kanab Creek Near Fredonia
9	Little Colorado River Near Mouth

To avoid transporting large volumes of water samples from the field to the Denver laboratory, the sand portion of the sample was run through a 230 (.062 mm) sieve-size screen and retained for transmittal to the laboratory. The clay and silt portion of the sample was run through a churn splitter in the field, and then the split sample was transmitted either on a filter or in a 500 ml bottle to the laboratory. During the 1983 and the 1985-86 sampling periods, 1,115 and 828 suspended sediment samples, respectively, were received in the Denver Interregional Soil and Water Laboratory for analysis.

A total of 874 discharge measurements were utilized in the sediment transport computations. The measurements made in 1983 at the sampling stations were scheduled for every other day, but because of crew changes, this schedule was not always possible. In 1985-86, more discharge measurements were taken than in 1983 to aid in defining the channel hydraulics for use in the sediment transport computations.

A total of 976 bed material samples taken in both sampling periods were used in developing average bed material sizes for the sediment transport computations. The number of samples or measurements taken in the two sampling periods and used in the computations described in this report are listed below.

Item	Number of Samples or Measurements		
	1983		1985-86
	Main Channel	Tributaries	Main Channel
Suspended Sediment	814	261	777
Bed Material	684		292
Discharge Measurements	259		615

SEDIMENT TRANSPORT COMPUTATIONS. The Modified Einstein Method (Colby and Hembree 1955), which relies on discharge measurements, suspended load samples, and bed material samples, is standard procedure for computing the total sand in transport at a sampling station. The results of our Modified Einstein computations provided data to develop total sand load rating curves at the five sampling locations and to test several of the many different predictive sediment transport equations for applicability to the Colorado River. The data needed for the Modified Einstein Method are stream discharge Q, mean velocity V, cross-sectional area A, stream width b, mean depth of cross section applicable to the EWI sampling verticals d, the measured sediment discharge concentration C, size distribution of the suspended load, size distribution of the bed material at the cross section, and water temperature. The predictive equation computations use the same data except for the suspended sediment load measurements.

Total sediment transport was computed using five applicable predictive transport equations:

Ackers and White (Ackers and White 1973)
Meyer-Peter and Muller (Meyer-Peter and Muller 1948; Randle 1984)
Toffaleti (Toffaleti 1969)
Velocity-Xi Adjusted Einstein, Bureau of Reclamation, (Einstein 1950; Pemberton 1972)
Yang (Yang 1973)

Computations by the Meyer-Peter and Muller Equation were limited to the 1983 data because the results were found to be from 80-90 percent lower than values shown by the other equations.

BED MATERIAL. The first step in the sediment transport computations was to develop a method for determining the appropriate bed material for use with the channel hydraulics and suspended sediment sample results. Consistencies existed in bed material sizes (ranging from sand to gravels and cobbles) in certain portions of each measuring cross section, with some minor changes occurring over time during the sampling period. For use in the sediment transport computations, bed material samples were composited by averaging data representing a determined portion of the cross section and time period. Each bed material composite was applicable to a particular river gage, cross section limits, and time period, with up to four bed material composites in a cross section.

A sampling problem was encountered when the BM-54 sampler would close on contact with gravel- or cobble-size bed material and fail to collect a sample. When this occurred, it was identified as a "no return" or "NR" sample. In some cases, when samples were collected near the interface where the bed material was changing from sand to gravel, samples had a few particles of coarse gravel and a small amount of sand. Some of these bimodal type samples were not used in computing a composite size gradation.

CHANNEL HYDRAULICS. Since the suspended sediment samples were not taken at or near the same time as the discharge measurements, especially in 1983, a method was developed for computing hydraulic parameters for use in the transport computations. A subdivision of the channel section was made with the same cross section distance limits as defined by the bed material composites. Subdivision of the section was accomplished by selecting a discharge measurement closest in time and gage height and adjusting the cross-sectional area to time of sampling by a change in gage heights. No change in velocity shown in the discharge measurement was made within a specified portion of the cross section. This technique provided a computed discharge for the suspended sample that could be subdivided into segments as defined by the change in bed material. The selection of a discharge measurement that could be adjusted for gage height and then subdivided for segmental discharge at time of suspended sampling worked better for the 1985-86 data because of the additional discharge measurements.

SUSPENDED SAMPLES. The suspended sediment concentration and size gradation represented the results of an EWI Method (U.S. Geological Survey 1978) of sampling. This permitted the compositing of all verticals sampled into one sample for laboratory analysis.

MODIFIED EINSTEIN METHOD. The computations of total sand load, using the Bureau of Reclamation's version of the Modified Einstein Method (Lara 1966; Stevens 1985), were done in parts because of significant variations in bed material across the sampling station. Hydraulic parameters such as discharge, area, velocity, top width, and wetted perimeter were computed for each subsection. The results of the Modified Einstein total load computation were used to develop a sand load rating curve at each sampling station as well as provide a check on the best predictive equation.

For all five of the Colorado River sampling stations, the first run for the Modified Einstein Method was made with "Z" slopes computed for the referenced size fractions having 1 percent or greater material in both suspension and bed material. After the first run, this percentage was sometimes changed in order to complete a computation and/or to have a better correlation for extrapolation purposes.

In the Modified Einstein computations, the suspended sediment load was subdivided within the cross section as identified by the type of bed material. The suspended sediment samples were composited from the EWI Method as sampled over the entire cross section width. The suspended sediment concentration and size were assumed to be the same in each subdivision of the water discharge and corresponding bed material. This assumption is considered good because of the interaction within the cross section caused by irregular bed forms, channel velocities, and turbulence. The meander pattern of the channel and variation of bed materials created by the meander in the vicinity of the five sampling stations also support the assumption that one composited suspended sediment sample is the same over all portions of the channel cross section.

The sand load portion of the Modified Einstein total load computation for each suspended sediment sample was plotted using a log-log scale of discharge in cubic feet per second versus sand load in tons per day. Examination of the data points plotted for 1983 and 1985-86 showed the overlap in discharges for the two periods in the vicinity of about 20,000 cubic feet per second (cfs).

MODIFIED EINSTEIN SAND LOAD REGRESSION CURVES. Total sand loads computed by the Modified Einstein Method were plotted and used to develop sand load rating curves by a least squares regression analysis (Chow 1964). The computed equations listed in Table 1 provide a representative average of the data points. Some scatter in data points occurred at all five sampling stations and can be traced to extremes in the suspended sediment sample results. Such extremes in samples from the Colorado river are not unusual for two reasons: (1) tributary or side drainage inflow of sediment, and (2) filaments of sediment movement in suspension caused by sand dune or sand bars influencing instantaneous samples. These factors create fluctuations in channel hydraulics and sediment transport parameters, and have a direct influence on variations in computed sand loads by the Modified Einstein Method.

Several conditions influenced the selection of the regression equations to be used (Table 1). One of the critical conditions was that the regression lines for any one sampling station should demonstrate continuity when compared to the sand load curves of the other stations. In this comparison, the extrapolation of the equations beyond the discharges measured at a particular station was a concern. To aid the reader in evaluating influences of other stations and problems of extrapolation, the sand load rating curves for all stations are shown in Figure 3. A station by station description of conditions considered in the final equations is shown in Table 2 and described in the following paragraphs.

Table 1. Colorado River transport study sand load rating curves, 1983 and 1985-86 data.

Location	Discharge Limits	Sand Load Equation - Tons/Day	Correlation Coefficient
1	0 cfs to 25,000 cfs	= 0.21029E- 11*Q**03.3326	--
1	25,000 cfs to Maximum	= 0.27301E- 14*Q**03.9864	0.897
3	0 cfs to 40,000 cfs	= 0.46047E- 10*Q**03.2228	0.915
3	40,000 cfs to Maximum	= 0.57336E- 05*Q**02.1117	--
4-6	0 cfs to 25,000 cfs	= 0.31854E- 10*Q**03.3326	0.898
4-6	25,000 cfs to Maximum	= 0.10114E- 04*Q**02.1117	0.675

Location 1 = Colorado River At Lees Ferry
Location 3 = Colorado River Above Little Colorado River
Location 4 = Colorado River Near Grand Canyon
Location 5 = Colorado River Above National Canyon
Location 6 = Colorado River Above Diamond Creek

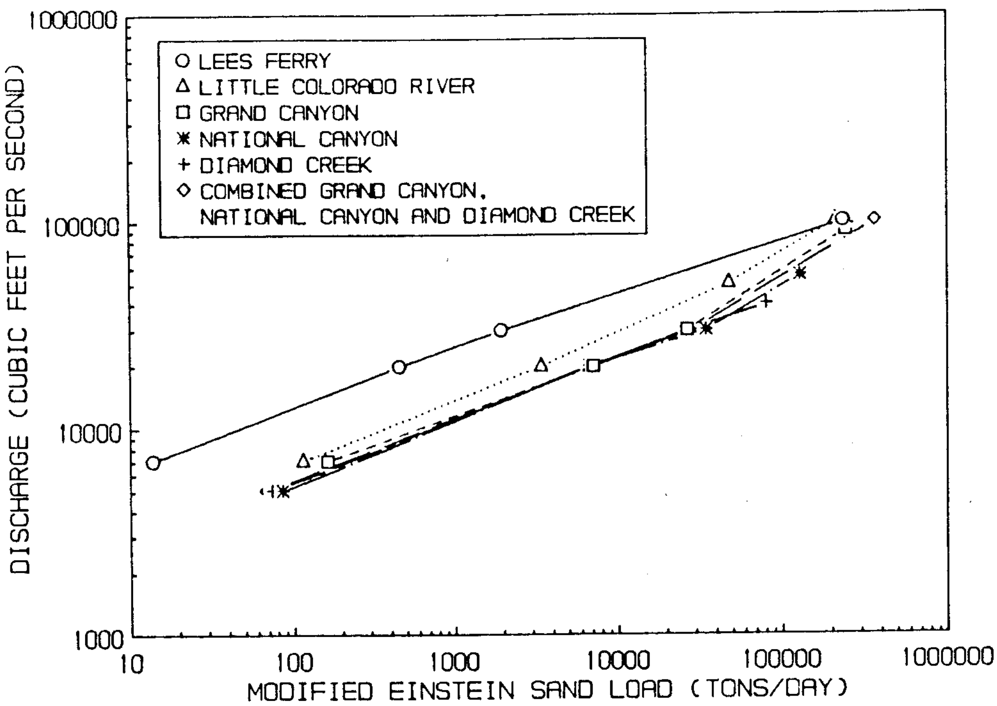

Figure 3. Modified Einstein sand load rating curves, Colorado River in Grand Canyon.

The data from At Lees Ferry (Location 1) indicated the use of two different equations: one for above and the other for below discharges of 25,000 cfs. The equation for below 25,000 cfs was influenced by relatively high suspended concentrations of sand-size sediments. Such data points were disregarded by extrapolating the regression line below 25,000 cfs parallel to the curves for downstream stations (which had more data for computing a line).

For Above Little Colorado River (Location 3), the break in data by discharge was moved up to 40,000 cfs (i.e., different equations were indicated for discharges above and below 40,000 cfs). This was done by examining the highest discharges and then extending upward to match the 100,000 cfs rating curve at Lees Ferry.

Near Grand Canyon (Location 4) data provided the most information at high discharges for extrapolating the equations for the downstream stations Above National Canyon (Location 5) and Above Diamond Creek (Location 6). Because of the need to extrapolate, and the

Table 2. Colorado River transport study sand load rating curves, 1983 and 1985-86 data.

Location	Method	Discharge - CFS Minimum	Discharge - CFS Maximum	Sand Load - T/D Minimum	Sand Load - T/D Maximum	Sand Load Equation	Correlation Coefficient
1	Modified Einstein	3360	91044	32	105,412	.27301E-14*Q**3.9864 (U)	0.897
						.66598E-04*Q**1.6439 (L)	0.672
	Ackers and White	9521	91044	19	82,589	.13267E-11*Q**3.4319	0.975
	Toffaleti	4181	91044	1	30,680	.71061E-10*Q**3.0132	0.926
	Velocity-Xi	9521	91044	4	92,726	.14979E-12*Q**3.5982	0.928
	Yang	9521	91044	25	134,096	.45951E-13*Q**3.7466	0.993
3	Modified Einstein	5249	57643	40	99,741	.46047E-10*Q**3.2228	0.915
	Ackers and White	5249	57643	5	17,470	.23621E-07*Q**2.5355	0.792
	Toffaleti	5249	57643	5	17,932	.99023E-07*Q**2.3675	0.766
	Velocity-Xi	5249	57643	5	25,963	.38124E-08*Q**2.6980	0.823
	Yang	5249	57643	8	15,171	.12184E-07*Q**2.5874	0.851
4	Modified Einstein	6319	83542	78	300,444	.31243E-04*Q**1.9961 (U)	0.732
						.21120E-11*Q**3.6104 (L)	0.913
	Ackers and White	6319	83542	126	104,377	.79606E-06*Q**2.2753	0.947
	Toffaleti	6319	83542	110	41,449	.41271E-05*Q**2.1074	0.924
	Velocity-Xi	6319	83542	181	431,531	.83662E-07*Q**2.5758	0.905
	Yang	6319	83542	76	117,219	.24605E-07*Q**2.5847	0.972
5	Modified Einstein	2969	55229	20	201,231	.86843E-05*Q**2.1448 (U)	0.645
						.18688E-09*Q**3.1519 (L)	0.882
	Ackers and White	2969	55229	20	236,351	.42876E-10*Q**3.3222	0.978
	Toffaleti	2969	55229	13	87,297	.13551E-10*Q**3.4223	0.974
	Velocity-Xi	2969	55229	36	792,483	.20423E-12*Q**3.9176	0.979
	Yang	2969	55229	19	186,380	.21843E-10*Q**3.3504	0.970
6	Modified Einstein	3807	39660	52	127,718	.35941E-12*Q**3.7706 (U)	0.566
						.67850E-10*Q**3.2542 (L)	0.896
	Ackers and White	5338	39660	9	132,900	.19110E-16*Q**4.7779	0.990
	Toffaleti	4006	39660	1	51,490	.26290E-17*Q**4.9594	0.989
	Velocity-Xi	3807	39660	1	284,999	.71860E-20*Q**5.6358	0.992
	Yang	4006	39660	1	46,224	.19834E-16*Q**4.7021	0.995
4-6	Modified Einstein	2969	83542	20	300,444	.10114E-04*Q**2.1117 (U)	0.675
						.31854E-10*Q**3.3326 (L)	0.898
	Ackers and White	2969	83542	9	236,351	.67790E-10*Q**3.2436	0.927
	Toffaleti	2969	83542	1	87,297	.36064E-10*Q**3.2951	0.915
	Velocity-Xi	2969	83542	1	792,483	.34449E-12*Q**3.8394	0.923
	Yang	2969	83542	1	186,380	.74576E-11*Q**3.4169	0.942

(U) - Upper Curve

} Split at 25,000 cfs

(L) - Lower Curve

extremely close comparison of the sand load rating curves at these stations, the data for the three stations were combined to compute rating curve equations for above and below 25,000 cfs applicable to all three locations (Figure 3 and Table 1).

ERROR ANALYSIS. The Modified Einstein Equations (Tables 1 and 2) represent total sand loads with many natural variations or errors in the data that could influence the results. These variations or possible errors involve the following: suspended sediment samples, bed material samples, discharge measurements, and laboratory analyses of suspended and bed material samples. Without tests for such errors for the Colorado River in the Grand Canyon (and more specifically at the sampling sites), all uncertainty caused by either errors or extremes in data are plus or minus and would, in general, cancel each other. Data from streams having medium to fine sand-size bed material show variations in error ranging from plus or minus 4 percent for discharge measurements to plus or minus 20 percent for Modified Einstein computations. For the Colorado River, average relationships were developed which should help cancel the errors involved in all possible factors. Modified Einstein results can vary from the computed regression lines because of time variations in sediment loads. Many of the apparent errors or variations are caused by natural factors that create fluctuations in the parameters used in the channel hydraulics or sediment parameters.

PREDICTIVE EQUATIONS. Upon completion of the Modified Einstein computations, the same bed material size analyses and hydraulic parameters were used in five different predictive equations to compute sediment transport. The only exception was in the application of the Meyer-Peter and Muller Equation (used with the 1983 data), but the equation gave consistently low sand loads and was not used when the 1983 and 1985-86 data were combined. The regression line equations for the predictive equations, as well as the Modified Einstein Equation, at the five sampling stations are listed in Table 2.

A comparison was made of the rating curves for all sand transport computations for the five sampling stations and the combined Locations 4, 5, and 6. The result of this comparison indicate that any one of the final four equations (excluding the Meyer-Peter and Muller) gives sand loads that agree favorably with the Modified Einstein sand loads.

In the Toffaleti and Velocity-Xi (adjusted Einstein) Equations, loads are computed by size fractions, which considers a hiding factor, while the sand loads computed by the Ackers and White and Yang Equations are based on a mean-size bed material with no hiding factor. There is a distinct advantage in using either the Velocity-Xi or the Toffaleti Equation in the STARS model on the Colorado River because the potential exists for armoring of the streambed with a sand-gravel mixture and these equations account for armoring (with a hiding factor). Other equations require an additional armoring analysis.

RECOMMENDATIONS

Sand load rating curves at the five sampling locations recommended for use as control in the STARS sediment routing model are given in Table 1. Based on comparison of sand load rating curves of the predictive equations, all of the four equations were found to adequately check the sand load computed by the Modified Einstein Method at all of the five sampling stations.

Either the Velocity-Xi (adjusted Einstein) or Toffaleti Equation, both of which rely on a hiding factor, would be more applicable for computing sand load transport in the STARS model than would the others. To reduce costs, it is recommended that the choice between these two equations to use in the STARS model be based on the least amount of computer time required.

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UNSTEADY FLOW MODELING OF THE RELEASES FROM GLEN CANYON DAM AT SELECTED LOCATIONS IN GRAND CANYON

This paper presents a discussion of the development of an unsteady flow routing model for the Colorado River below Glen Canyon Dam at five locations in Grand Canyon National Park, Arizona.

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INTRODUCTION

During regimes of average or near average inflow to Lake Powell, the powerplant at Glen Canyon Dam is operated on a demand-load basis. This results in a pattern of high (31,000 cubic feet per second [cfs]) releases in the afternoon and low (3,000 cfs) releases in the early morning. As flows proceed downstream, they develop into a diurnal, almost sinusoidal, flow hydrograph. This daily rise and fall of the river is well known to commercial boatmen and others familiar with the river. As surges of flow proceed downstream, they are modified by temporary changes in channel storage. The peaks tend to diminish in magnitude, while the troughs increase in magnitude. In addition, flows of higher discharge travel faster than those of lower discharge, resulting in a modification of the hydrograph.

One of the objectives of the Glen Canyon Environmental Studies (GCES) is to evaluate present and potentially different modes of operating the powerplant. In order to accomplish this, it was necessary to develop a technique for estimating flows from Glen Canyon Dam at important locations along the 240 miles between the dam and Diamond Creek. With this information, other participants of the GCES could determine how the different flow scenarios impacted the beach, recreational, and biological resources of the canyon. An important secondary need was to provide users with estimates of discharge at study locations in the canyon during periods of field data collection.

MODEL SELECTION AND DEVELOPMENT. Modeling unsteady flow has always been a difficult and challenging problem. Even with the availability of high speed computers, most models are difficult to use because of the large amount of cross section data required. For example, the Dynamic Wave Operational Model (DWOPERS), a program developed by the National Weather Service, is data intensive. Conversely, The Streamflow Synthesis and Reservoir Regulation (SSARR) model is a flow routing model that can be developed from a limited set of data. It was therefore chosen to provide unsteady flow modeling for releases from Glen Canyon Dam for the GCES research.

Developed initially to meet the needs of the North Pacific Division of the U.S. Army Corps of Engineers, the SSARR model has been in use since 1956. It provides mathematical hydrologic simulations for system analyses required for the planning, design, and operation of water control works. The SSARR model was further developed for operational river forecasting and river management in connection with the cooperative Columbia River Forecasting Unit, sponsored by the National Weather Service, U.S. Army Corps of Engineers, and Bonneville Power Administration. In recent years, various agencies, organizations, and universities have modeled numerous river systems in the United States and abroad with the SSARR program.

The successful application of the SSARR model is dependent upon derivations of the various parameters and relationships specific to a particular river system. Streamflow characteristics are primarily determined by trial-and-error solutions with the computer program to obtain the best fit of historical streamflow data. This procedure is repeated until adequate verification of observed flows is obtained and the characteristics tested with independent data.

Proper characterization of channel routing provides an integrated response of river system entities to hydrologic input. The program allows considerable flexibility in determining routing coefficients which simulate downstream peaks and timing response. Channel routing can be accomplished with either a routing equation for incremental routing, or a table which specifies time of storage-discharge relationships.

The time rate of change of streamflow in a river reach is evaluated by first dividing the reach into a series of small increments. Inflow to the uppermost reach is the release from Glen Canyon Powerplant during an increment of time (in this case, one hour). The program then uses a variation of the standard storage routing equation to compute the outflow from the first increment. This flow value becomes the inflow to the next reach of stream. Computations proceed downstream in this manner until the lowermost reach is met, after which the computations begin for the second hour (U.S. Army Engineer Division 1972 [revised June 1975]). To calibrate the model, it is necessary to vary three parameters (number of routing phases, time of storage per phase, and dimensionless coefficient) until the computed flows agree as closely as possible with the recorded flows.

METHODS

During the winter of 1985-86, the U.S. Geological Survey operated five data collection stations between Glen Canyon Dam and Lake Mead (Figure 1). The station called "Near Grand Canyon" is located above Bright Angel Creek at River Mile (RM) 87.5. Data pods or continuous recorders were established or were already in place at each site. Standard streamflow measurements were made during the data collection period (Table 1). The period of record common to all five stations is October 5, 1985, to November 11, 1985. During this time period, releases followed a diurnal pattern and ranged from 1,100 to 22,000 cfs. A rating table was developed for each site which allows for the conversion of the flow depths to a record of hourly streamflow discharge.

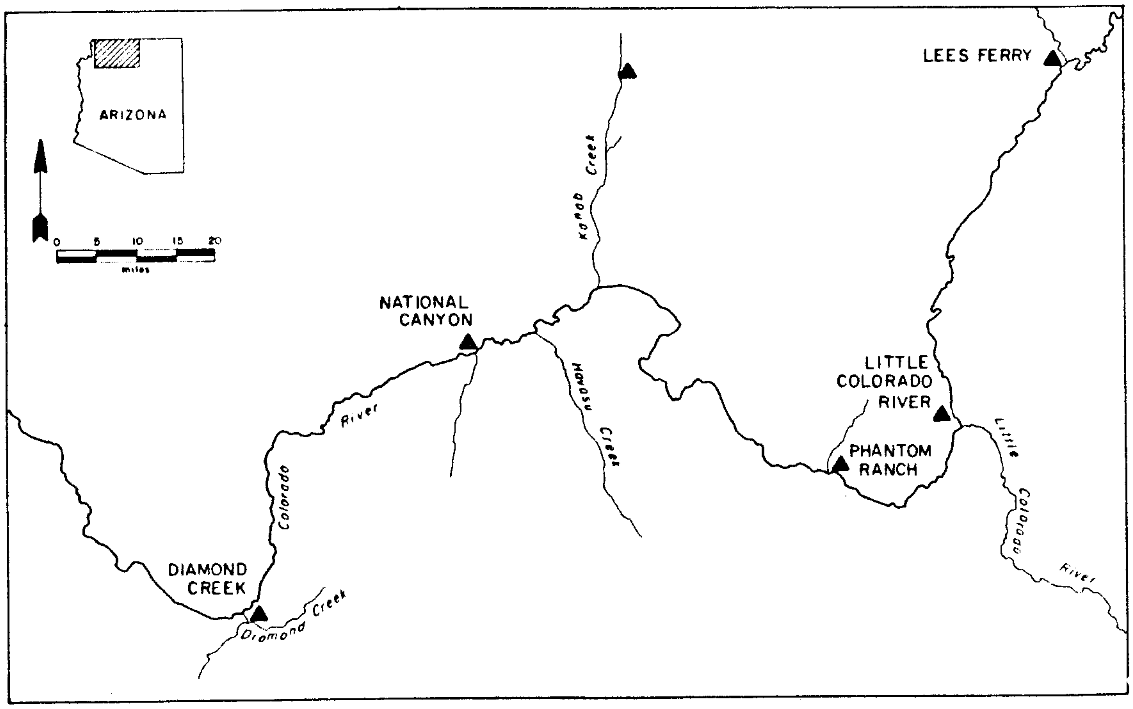

Figure 1. Map of the Colorado River through Grand Canyon National Park with location of gaging stations.

Table 1. Periods of streamflow measurements.

Station	River Mile	Period of Operation
Lees Ferry	0	Full period (permanent gage)
Above Little Colorado	61	October 1, 1985 - November 11, 1985
Near Grand Canyon	87.5	Full period (permanent gage)
Above National Canyon	166	October 2, 1985 - December 19, 1986
Above Diamond Creek	225	October 5, 1985 - November 11, 1985

Several steps are followed to configure the SSARR model. The uppermost station is Glen Canyon Dam. Hourly releases at the dam are input and the model computes corresponding flows at Lees Ferry. The recorded flows at Lees Ferry are then input and the computer program compares computed and recorded flows in both tabular and graphic format. The operator then changes the value, either the number of the routing phases or phase storage time of model coefficient, and makes another run. He then compares results with the previous run to determine if the change has improved the reconstitution of the observed flows. After many iterations, a point is reached where improvements are negligible and the operator begins calibration of the next downstream station, i.e., Above Little Colorado. The input used for that calibration are the computed flows at Lees Ferry. The process continues down to the Above Diamond Creek station, after which the model is considered fully calibrated and ready for production runs.

The SSARR model has the ability to handle tributary inflows. However, this feature was not used since the magnitude of the flows of the Paria River, the Little Colorado River, and Kanab Creek is generally much less than the discharge in the main channel. The model preserves the volume of flow as it passes from one station to the next, so that there are no losing or gaining reaches of river unless the operator inputs such a situation.

The SSARR model as now configured will compute flows directly only at the stations used in its calibration. Estimates of flow elsewhere require an interpolation process (described in the results section). The final model runs for each of the five stations are presented in the technical GCES report.

There are three advantages to using the SSARR program to model unsteady flow releases in Grand Canyon: (1) cross-sectional and other surveyed data are not required; (2) the model can be calibrated with observed data that have been collected over fairly short intervals of time, provided that the model is not applied to a range of flows too far outside those observed; and (3) the model is easy to develop.

There are also three disadvantages: (1) the model assumes a constant travel time between stations regardless of flow magnitude. This is probably the most serious disadvantage of applying the model to diurnal flows in the Grand Canyon. It is a well-observed and recorded fact that peak flows travel downstream faster than trough flows. (2) Since the input of one station is the computed output from the upstream station, errors tend to accumulate as computations proceed downstream. (3) Flows can only be computed directly at the stations used in the original calibrations.

An example of the error associated with the use of the model is shown in Table 2. The model as it is now configured has several biases. First, it tends to underpredict peak flows by as much as 700 to 1,100 cfs on the average. However, this corresponds to only 0.2-0.4 ft of stage. Second, it tends to predict the arrival of a peak discharge about one hour later that it should. Third, the troughs tend to be estimated several hundred cfs higher than they should be, but in terms of stage this error is again on the magnitude of only 0.2-0.3 ft. And fourth, it predicts the arrival of the trough about one hour sooner than it should. If the exact magnitude and times of the predicted peaks and troughs are essential to the user of this model, he or she is advised to make these adjustments to the computed data results.

The following example illustrates the SSARR model's veracity. Assume that a surge of water is released from Glen Canyon Dam. After it has traveled 48 hrs to Diamond Creek, 240 miles downstream, the model incorrectly predicts the peak discharge by 0.4 ft (plus or minus 0.2 ft). In a flow hydrograph, this is shown by a fluctuation of as much as 10 ft. This error may be tolerable for most, if not all, users.

Ideally an independent set of data should be used for an error analysis. However in this case, the only information available outside the calculation period is from the gages at Lees Ferry and Grand Canyon.

Table 2. Error analysis. *

Station	Peaks			Troughs		
	Magnitude (cfs)	(ft)	Timing (hours)	Magnitude (cfs)	(ft)	Timing (hours)
Lees Ferry Station (33 events)						
Mean Difference	10	0.0	0.1	60	0.0	-0.8
St. Dev. of Differences	160	0.1	0.6	240	0.1	0.5
Little Colorado (20 events)						
Mean Difference	-900	-0.3	1.2	320	0.2	-0.9
St. Dev. of Differences	530	0.2	1.0	220	0.1	0.6
Grand Canyon Station (32 events)						
Mean Difference	-720	-0.3	1.2	260	0.2	-0.9
St. Dev. of Diffferences	460	0.2	1.0	260	0.2	0.9
National Canyon Station (32 events)						
Mean Difference	-700	-0.4	1.1	260	0.3	-0.7
St. Dev. of Differences	460	0.2	1.0	260	0.3	1.0
Diamond Creek Station (28 events)						
Mean Difference	-1130	-0.4	1.3	820	0.3	-1.1
St. Dev. of Differences	500	0.2	1.3	410	0.2	0.6

* Negative values indicate that predicted events are smaller in magnitude or occurred earlier in time than the recorded ones.

RESULTS

Hourly values of releases from Glen Canyon Dam for the period July 1983 through September 1986 were run through the model to give estimates of hourly flow at the five downstream stations. It is not practical to reproduce these data in this report, as they comprise nearly 170,000 flow values. However, the data are available on a floppy disk. Temporarily, the data can be accessed from a public file on the Bureau of Reclamation's CYBER system.

Hourly values of releases from Glen Canyon Dam for the following five powerplant operation alternatives suggested by the Bureau of Reclamation were input and run through the model (except for the baseload scenario for which the flows are constant).

Alternative 1. Releases would be baseloaded with no daily fluctuations in any given month. Monthly flows would vary, ranging from 8,300 cfs in March to 14,600 cfs in January.

Alternative 2. Flows would fluctuate daily, monthly, and seasonally, ranging from 1,000 cfs to 31,500 cfs. Average monthly releases would range from 8,300 cfs in March to 17,000 cfs in July.

Alternative 3. Average amount released each month would be similar to that in Alternate 2, but with higher minimum and lower maximum releases. Flows would range from 8,000 to 25,000 cfs.

Alternative 4. Releases would be a steady 25,000 cfs during the recreation season (June-August), but would fluctuate from 1,000 cfs to 31,500 cfs the remainder of the year. Average monthly flows would range from 4,900 cfs in March, May, and October, to 25,000 cfs in the summer.

Alternative 5. Designed to benefit the fishery, this release pattern features low, relatively steady winter flows of 8,000 to 8,900 cfs. Releases would only fluctuate from 6,000 to 10,000 cfs. Most of the rest of the year, flows would be greater, with average monthly releases ranging from 12,200 cfs in May to 17,000 cfs in July. Fluctuations would also be greater, ranging from 1,000 to 31,500 cfs.

These data are also available on disk or temporarily on the CYBER.

As stated previously, the model can only predict flows at the locations for which it was calibrated. However, it has been observed that once flows reach Lees Ferry, the peaks and troughs tend to diminish and increase, respectively, in a nearly linear manner with distance. To obtain estimates of hourly flow at other locations on the river, it is proposed that a straight line interpolation technique be used. For example, assume that the user wishes an estimate of flow at 1300 hours on October 15, 1984 at RM 17. The user consults a table of travel times (Table 3) of peaks and troughs to each of the five gage locations for the computed flows for the October 5 to November 8 (year) period. Again, note that the estimates ignore the fact that peaks travel faster than troughs.

Table 3. Travel time of Glen Canyon Dam releases.

Gage Locations	Time (Hrs)	Standard Deviation
Glen Canyon Dam to Lees Ferry	3.0	1.3 hrs
Lees Ferry to Little Colorado River	14.5	1.5 hrs
Little Colorado River to Grand Canyon	3.9	0.7 hrs
Grand Canyon to National Canyon	14.9	1.8 hrs
National Canyon to Diamond Creek	11.3	1.0 hrs

The distance between Lees Ferry and Little Colorado River is 61 river miles. To determine the estimated flow at RM 17, multiply the time of travel for Lees Ferry to Little Colorado River (14.5 hrs) by the fraction of distance the water travels (17 miles divided by 61 miles) as in the computation below:

$$(14.5)(17/61) = 4.04 \text{ hrs}$$

The user goes to a table of computed flows for Lees Ferry and determines the value there for 0900 hours (1300 hours minus 4 hrs [rounded off from 4.04]). Then, the user goes to the table of computed flows at Little Colorado River and determines the value for 2300 hours (1300 hours plus 10 hrs [rounded from 14.5-4.04]). The two values are then averaged to get the desired estimate of flow at RM 17.

CONCLUSIONS

The Streamflow Synthesis and Reservoir Regulation (SSARR) model was modified to allow for the calculation and prediction of discharge and stage levels in the Grand Canyon. The modification of the model centered on matching discharge volumes, peak and trough hydrograph timing, and magnitude downstream at five gages located within the Grand Canyon for specific periods of actual streamflow data collection activities.

The data used to initialize the model consisted of actual hourly flow releases from Glen Canyon Dam. The model then computed the volume, timing, and stage of the discharge at the five downstream gaging stations. Calibration of the model was performed by a best-fit process, utilizing variations in the routing phases, time of storage per phase, and in calculation coefficients. The model has several biases that need to be understood before a rigorous use is made of the results:

(1) The model underpredicts peak discharge levels by 700 to 1,100 cfs.
(2) The peak discharge levels are predicted to arrive at the gaging stations on an average of one hour later than actual measurements.
(3) The trough discharge levels are predicted to be up to 200 cfs higher than the actual measurements.
(4) The trough discharge levels are predicted to arrive one hour earlier than actual measurements.

For a majority of GCES study requirements, these biases should not be a problem. To estimate the hourly flows at study sites other than the five gaging station locations, a straight line interpolation technique was developed. It requires the knowledge of time of travel, time of discharge releases, actual dam discharge levels, and location of the required study site relative to the nearest gaging station.

The SSARR model has been adapted for use in Grand Canyon to predict unsteady flows at five locations below Glen Canyon Dam in Grand Canyon. A computer program has been developed using the SSARR predictions to estimate flows at locations between the gages and is available to the public.

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SEDIMENT TRANSPORT AND RIVER SIMULATION MODEL

This document summarizes the development and application of the STARS model to sediment studies in the Grand Canyon. The methods used to compute water surface profiles, determine streamtube hydraulic properties, and calculate sediment transport capacity are discussed, along with routines to mix transported and in-place sediment, and update cross section geometries.

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INTRODUCTION

The U.S. Bureau of Reclamation's Sediment Transport and River Simulation (STARS) model was developed to mathematically simulate the movement of water and sediment through alluvial river channels. Several unique features were added to this one-dimensional, steady-state model to support the modeling efforts on the Colorado River in the Grand Canyon. One such feature is the use of streamtubes to vary the hydraulic and sediment transport characteristics across a cross section. This allows a more defined representation of sediment movement. For example, scour can be modeled in one streamtube while concurrent deposition occurs in another tube. Features were also developed for routing water and sediment in channels where rapids or bedrock outcrops occur. Because all incoming sediment to the study reach of the Grand Canyon is supplied from tributary inflow, routines were included to increment water and sediment discharge at any location in the reach. Additional routines were developed to vary initial bed material in three dimensions (longitudinal, lateral, and vertical). Bed material size gradations can be different at each cross section, varying laterally across a given section by streamtube, and varying vertically by layers within a streamtube. The Colorado River in the Grand Canyon has provided a difficult testing ground for the STARS model with flow conditions ranging from rapids at critical flow to slower velocity pools, and bed material ranging from bedrock to fine sand.

METHODS

OPERATIONAL CONCEPTS. The STARS model may be used to perform either a fixed or movable bed hydraulic analysis. When STARS is used as a fixed bed model, no sediment data are required and water surface profiles are computed assuming an unchanging bed.

When a movable bed analysis is desired, the user must provide a discharge hydrograph (described by a series of discharges and corresponding time steps). A steady-state water surface profile is computed for the initial discharge of this hydrograph. Using these water surface elevations, each cross section is divided into streamtubes of equal discharge, and hydraulic properties are determined. The incoming sediment load to the study reach can be entered as a sediment load hydrograph, sediment-discharge rating curve, or (as a default) the model will compute a sediment transport rate in each streamtube based on initial hydraulics and bed material size gradations at the upstream-most section. Sediment transport rates are then computed for each streamtube at each cross section, and the amount of scour or fill is determined. Finally, a new size gradation of the bed is computed, and the cross section coordinates are adjusted. Then the model proceeds through the rest of the discharge hydrograph in a similar manner.

The STARS model is one-dimensional, meaning no attempt is made to simulate secondary currents in the hydraulic calculations or to compute sediment transport between streamtubes. Sediment transport routines are developed for sand or gravel bed channels and applications at present are limited to non-cohesive, coarse-grained materials.

DATA COLLECTION AND STARS INPUT. Specific field data needed to execute the fixed bed or hydraulic portion of the STARS model are similar to the data required for any of the available water surface profile computer programs. Geometric data that define the channel shape include cross section profiles, channel reach lengths between sections, and roughness coefficients. Channel roughness values across a section are segmented with corresponding lateral coordinate endpoints and longitudinal reach lengths. The upstream boundary is specified as a discharge hydrograph and the downstream boundary is specified as either a stage- or slope-discharge hydrograph. The only additional input is the number of streamtubes, which gives the user the ability to further define the channel velocities and associated sediment transport capabilities across the section.

In order to run the movable bed portion of the model in conjunction with the hydraulic computations, additional sediment data are required. Basic input include representative sediment size gradations of the streambed material at each cross section. The user can vary the bed material size gradations in three dimensions. An incoming sediment load hydrograph or sediment-discharge rating curve, corresponding to the water discharge hydrograph, is required along with the water temperature hydrograph to provide the upstream boundary conditions. A sediment transport method or algorithm must be selected which best fits the river conditions or available data in the study reach. Limits on the depth of degradation can be supplied by the user for the case where there is a known grade control or bedrock elevation below the streambed.

STARS OUTPUT AND REPORT GENERATOR. The output from the model can vary significantly from a fixed bed to movable bed analysis with the intent of the user. Therefore, a separate report generator was developed to summarize large quantities of computational output. Output tables are designed by the user to meet specific needs. Example output would be information for a given cross section on a page with a user-defined choice of hydraulic or sediment transport parameters for column headings and time incrementing in rows.

WATER SURFACE PROFILE COMPUTATION. Water surface elevations are computed assuming steady-state conditions using the standard step method. An upstream boundary discharge hydrograph and a downstream boundary elevation are required by the model. The downstream elevation may be expressed as a stage-discharge rating curve, an elevation hydrograph, normal depth (slope-discharge relationship), or critical depth. Unsteady open channel flow analysis is not used because of prohibitive computational time and cost.

From the water surface elevation at the downstream-most section, calculations proceed upstream satisfying the conditions of conservation of energy unless critical discharge occurs. The friction slope is computed using the Manning's Equation. A Newton algorithm with special checks for convergence problems is used to solve the energy balance, normal depth, and critical depth equations.

The energy balance is voided when the computed water surface elevation has an adverse water slope or is below the critical elevation. When an adverse water slope is computed, the upstream water surface elevation is set equal to the downstream water surface elevation. When the computed water surface elevation is supercritical, the model brings the water surface up to the critical depth.

The main channel flow may be increased in the case of tributary inflow or decreased in the case of a diversion. The change in discharge is considered to occur at a point between cross sections. The user provides the main stem discharge hydrograph at the upstream-most cross section and incremental flow hydrographs (positive for inflow and negative for outflow) are added to the main stem flow.

STREAMTUBE CONCEPT. The mathematical basis for routing water and sediment in streamtubes begins with two definitions from Chow (1964): (1) "A streamline is an imaginary line within the flow for which the tangent at any point is the time average of the direction of motion at that point," and (2) "A streamtube is a tube of fluid bounded by a group of streamlines which enclose the flow."

The streamtube is bounded by the channel geometry, the water surface, and the vertical streamtube divisions (Figure 1). This mathematical approach divides the flow into segments of equal conveyance and discharge. By calculating sediment transport in streamtubes, the distribution of the sediment transport across the section can be obtained. In this manner, transport rates calculated in overbank areas are lower than those for the main channel, as would be expected.

Streamtube boundaries are determined after the water surface elevation is computed for a given time step and discharge for the cross section as a whole. The total conveyance, summed from increments between individual coordinate points, is divided by a user-supplied number of streamtubes (maximum of ten). The lateral locations of the streamtube boundaries are interpolated between cross section coordinate points. The area, wetted perimeter, and top width can then be calculated for the individual streamtubes. These parameters, together with slope, velocity, and bed material gradations, are essential to computing sediment transport.

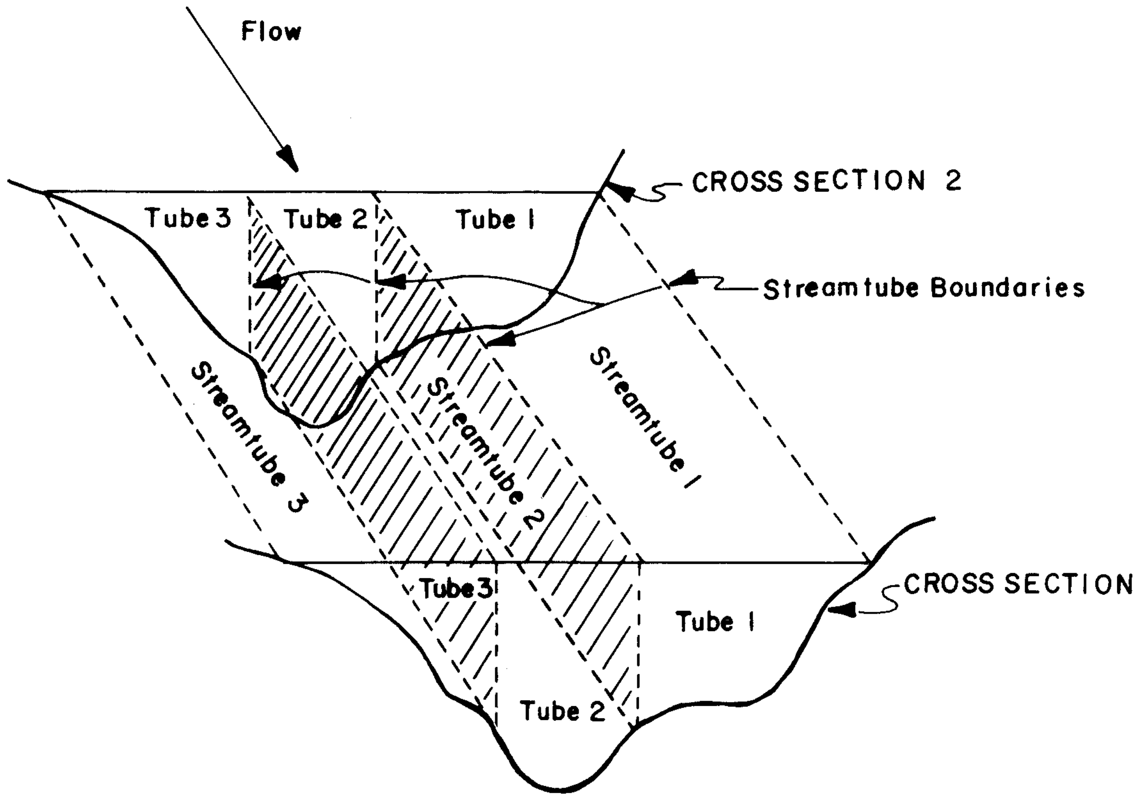

Figure 1. Three-dimensional plot of a channel with three streamtubes.

SEDIMENT TRANSPORT COMPUTATIONS. A number of sediment transport equations have been developed from flume and river data, based on bed material ranging from medium gravel to very fine sand. The predictive equations programmed into the STARS model are: Meyer-Peter and Muller (1948) based on U.S. Bureau of Reclamation (1960; Randle 1984) investigations (this will be a future addition); Einstein's (1950) Bed-Load Function based on the Velocity-Xi Adjusted Einstein Equations (Pemberton 1972; U.S. Bureau of Reclamation 1963); Engelund and Hansen (1967) (this will be a future addition); Toffaleti (1968, 1969) adaptation of the Einstein Bed-Load Function; Yang (1973) with the updated gravel bed equation from Yang (1984); and Ackers and White (1973).

A distinction is made in the model between the sediment transport capability of a given river flow for a certain sediment mixture and actual availability of sediment supply. The transport equation predicts total bed material load for each of the size ranges in the bed based upon hydraulics for a certain discharge and time step. The sediment transport is considered to be supply-limited when there is insufficient material available from upstream and in the bed to supply this calculated transport capacity. The supply routine checks the availability of sediment, and when the transport is supply-limited, the model automatically reduces the transport rate, based upon capacity, to the supply-limited rate.

The ability to add sediment from tributary inflows was included with the movable bed portion of the model. Input of the incremental sediment can be in the form of a sediment discharge rating curve, or a sediment load or concentration hydrograph. The model weights the sediment supply in each streamtube by velocity. Higher velocities in the main channel would thereby contain larger portions of the incoming sediment load. Water temperature data can also be included with the incremental sediment supply since water temperature can affect viscosity and, in turn, sediment transport. Temperature data from tributary inflows are discharge-weighted with the main channel.

CROSS SECTION UPDATING ROUTINE. The critical link to making the STARS model accurately simulate a movable bed is the ability to apply the predictive sediment transport calculations to the cross section coordinates. Sediment transport calculations proceed in the downstream direction matching the physical movement of water and sediment. For each of the streamtubes, sediment transport rates are compared between the upstream and downstream sections and a net sediment flux is computed for the subreach between the two sections. Using the bulk density for sand, a volumetric change can be computed from the net sediment flux. Dividing the volumetric difference by the effective distance between sections gives a new change in cross-sectional area to be applied to the coordinate points in the streamtube. After a net change in elevation is computed for each streamtube, the cross section coordinates are adjusted across the entire cross section. The elevation adjustment is the same for all coordinates within a streamtube but the adjustment is different for each streamtube.

ACTIVE LAYER AND TIME STEP. The sediment transport process is a gradual sorting and mixing of the incoming sediment load with the existing bed material. A certain thickness of bed material, or active layer, is considered to be in a state of flux at any cross section and time step. The thickness of the active layer must have some relationship to the height of bed-forms in the channel (Bennett and Nordin 1977).

In the STARS model, the active layer is a function of the hydraulic depth, which is considered to be a first approximation to the height of bed-forms in the channel. To date, active layer thickness in the model has ranged from 10-30 percent of hydraulic depth. While this relationship may underestimate some bed-form heights and overestimate others, it is practical for modeling because too small an active layer would severely reduce computational efficiency (increase modeling cost), and too large an active layer would introduce too much error. Once the active layer is computed, an appropriate time step is determined.

A time step is the period for which the model will apply transport rates to scour-and-fill computations before the cross section geometries and bed materials are updated. The model's time steps are limited by either the user-specified time step or the minimum time in which any one streamtube scours or fills to a depth equal to its active layer thickness. The user provides a hydrograph of water discharges and corresponding time steps (major time steps). When this time step results in a scour or fill depth greater than the active layer, it is automatically divided into smaller (minor) time steps. The minor time step for all cross sections is computed so that the limiting tube and cross section will have a scour or fill depth equal to the active layer thickness.

When fill occurs, an inactive layer is established and maintained in a manner similar to the method used by Bennett and Nordin (1977). The inactive layer is used to keep track of the gradation and thickness of the fill material between the active layer and the original bed. This feature of the model may also be used to represent a river with two bed material layers of different gradations. In this case, the surface bed material gradation and its thickness are assigned to the active and inactive layer while the underlying bed material gradation is assigned to the original bed. Once the surface bed material has been scoured, the model will begin using the underlying bed material gradation.

MIXING OF BED MATERIAL SEDIMENT. Accounting steps and checks are undertaken in the mixing routine to mix incoming sediment with the streambed and maintain proper gradations across the section and through the vertical by streamtube. A new size gradation of the streambed is determined from a mass balance (by size fraction) of the incoming sediment, sediment in the active layer, and sediment passing the cross section.

The first step in determining a new bed material size gradation is to determine the proper bed material for each streamtube by selecting the dominate size gradation within the streamtube. Size gradations in dry overbank areas are kept the same. The fraction of material in the active layer is computed for each streamtube using the initial or old bed material size gradation and the initial active layer thickness (based on a percentage of the hydraulic depth). The total supply or source of sediment is computed for each size fraction for a given streamtube by adding the incoming sediment to the material in the active layer. If the bed material is bedrock or the material is too coarse to transport, the supply is set equal to the transport of the upstream cross section. New active and inactive layer depths are determined, based upon the amount of scour or fill, and used to compute a thickness-weighted gradation to be applied at the end of the time step.

A base gradation is used to keep track of the gradation below the inactive layer. When the bed has scoured through the upper bed material zone or inactive layer, the underlying bed material is used. The base gradation is updated whenever the bed has scoured to a new minimum elevation and subsequently fills. If the initial active layer is completely removed, the bed material size gradation is adopted from the inactive layer. When there is no inactive layer, then the bed material size gradation is set equal to the base or underlying size gradation.

The model allows fill to occur on bedrock only if the Froude number and velocity, at a given section, are less than 95 percent of those computed for the next upstream section. Also, a maximum threshold velocity above which material will be carried over the bedrock is determined in the model by letting sediment deposit on bed rock and then applying the sediment transport equation during the next minor time step to see if the material will be either removed or continue to fill. In the interest of computational efficiency, the user may provide the model with a predetermined threshold velocity for which there is certainty throughout the simulation that any material deposited upon bedrock would be immediately removed during the next time step.

Once the cross section geometry and size gradation are updated, the minor time step is finished and the next time step begins with the computation of a new water surface profile. New velocities and size gradations will be used in the next computation of sediment transport. Thus, for a given discharge, rates of scour or fill will decrease with time.

MODEL LIMITATIONS. The greatest limitations to effectively using the STARS model are level of experience of the user, time, and money. The model also has limitations concerning deficiencies of input data, bank erosion, and application to fine-grained streambeds (silts and clays). Lack of good input data is frequently a limiting factor in modeling. Adequate input data describing the initial channel geometry, initial bed material size gradation, and upstream boundary water and sediment supply (including tributaries) for the study reach are requisite for proper application of the STARS model.

Data are also useful, if not required, to calibrate or verify various aspects of the model. Observed water surface elevations for a known discharge are needed to calibrate the Manning's n roughness coefficient. Ideally, Manning's n should be calibrated for the range of discharge used in the river simulation. Also, suspended sediment, bed material size gradations, and hydraulic data (at the upstream boundary) influence the choice of a sediment transport equation. Finally, field measurements of actual river conditions are necessary to verify or calibrate the input data used in predictive river simulations. These data might include sediment outflow from the study reach, initial and ending conditions of channel geometry and/or bed material size gradations, and/or observed surface elevations.

The STARS model can predict different rates of scour-and-fill for each streamtube, but it does not specifically address bank erosion. For rivers where bank erosion or river meandering is of extreme importance, use of the STARS model is not recommended.

The STARS model is not applicable to a cohesive or fine-grained streambed because the sediment transport equations presently in the model apply only to sand-size or larger sediments. The ability to model the armoring process is also limited by the chosen sediment transport equation.

In general, the STARS model predicts that as the streambed fills, the bed material will become finer and velocities will increase, and as scour occurs the streambed will coarsen and velocities decrease. Thus, for a given discharge, rates of scour or fill as computed by the STARS model will decrease with time. However, no provision is made to change the Manning's roughness coefficient with changes in bed material.

MODEL ABILITIES. With the critical depth constraint, the STARS model has the ability to model steep channels with continuous water surface profiles. Rapids in natural rivers are composed of a series of hydraulic jumps distributed in a seemingly random pattern across the channel, and it is not realistic to simulate this system as one hydraulic jump representing average conditions across a channel. All of the energy dissipation in a natural river does not occur in one hydraulic jump, and it is reasonable to approximate the water surface profile through a rapid by limiting the elevation to the critical depth.

As few as one or as many as ten streamtubes can be used to vary hydraulic and sediment parameters across the channel. The user should be aware that modeling costs increase with the number of streamtubes and the number of streamtubes should be related to the amount of input data.

The STARS model can be used to perform river simulations with either a fixed or movable streambed. Initial bed material size gradations can be varied in the longitudinal, lateral, and vertical dimensions. For the movable bed portion of the model, instantaneous rates of scour or fill are applied to discrete increments of time.

The STARS model seeks to balance the sediment transport rate at each cross section for a given streamtube and discharge. This is done by adjusting both the channel geometry and bed material through the scour-and-fill process. Therefore the model compensates for small errors in the input data by automatically adjusting the channel geometry. For example, if a computed velocity at a given streamtube were higher than the actual velocity, scour would occur and the velocity would decrease. The user should note that river simulations must be long enough so that one can be sure that channel adjustments are not continuing to be made to account for errors in the input data.

Data preparation is designed to be simple and easy, with redundancies kept to a minimum. For example, any number of cross sections can be input and in the upstream or downstream order. Up to 200 pairs of X and Y coordinate points can be input/cross section.

RESULTS

USING EAST FORK RIVER DATA. Hydraulic and sediment transport routing schemes were first coupled in the STARS model to reasonably predict changes in the bed profile on the East Fork River near Boulder, Wyoming. A 3,213 meter reach was modeled for a 30-day period using 39 surveyed cross sections. The median diameter of the bed material ranged from .39 mm to 14.3 mm. The RMS (root means square) error between the measure and predicted thalweg profiles was .17 meters.

USING GLEN CANYON DATA. The reach of the Colorado River between Glen Canyon Dam and Lees Ferry was chosen for verification and sensitivity testing of the STARS model. River simulations would later be made on the Colorado River below Lees Ferry. Cross section data were available for the reach prior to closure of the cofferdam and during the degradation monitoring (Pemberton 1976). The upstream sand sediment supply was considered to be cut off (zero) with the closure of the cofferdam, causing the flow to degrade the streambed.

A 6.6-year period (from February 11, 1959, to September 30, 1965) following the closure of the construction cofferdam was simulated. The hydraulic geometry was obtained from 23 cross sections collected in 1956. It was assumed that these cross sections did not change until closure of the construction cofferdam three years later. Half of these cross sections were resurveyed ten months after the closure, and all were resurveyed in 1965. This provided two checks on the predictions of the STARS model. Bed material samples of the surface layer, underlying layers of sand, and subsequent layers of gravel were taken at the same time (Pemberton 1976).

For simulations of the Colorado River below Glen Canyon Dam, transport equations using a hiding factor were found necessary to properly model the armoring processes occurring in the reach. Both the Velocity-Xi adjusted Einstein Equations and Toffaleti adaptation of the Einstein Bed-Load Function were programmed into the STARS model and tested. It was evident in simulation runs for the 10-month period on the reach from Glen Canyon Dam to Lees Ferry that the Toffaleti version would provide similar and reliable results at about half the cost. The Toffaleti formulation was therefore used for the longer 6.6-year period.

The model overpredicted the volume removed in the upper portion of the reach from cross section S-0 to S-9 and underpredicted the material removed in the lower portion of the reach from S-9 to the Paria Riffle. The overall prediction of volume removed was within 11 percent of the measured volume. Having successfully predicted the degradation below Glen Canyon Dam, the STARS model could be used to continue simulations on the reaches in the Grand Canyon.

SENSITIVITY ANALYSIS OF THE STARS MODEL. The STARS model was chosen as a tool to determine the relative impacts of Glen Canyon Dam Powerplant operations on the Colorado River in the Grand Canyon. To accomplish this task, over 700 cross sections were used to model 225 miles of river. This is one of the largest movable bed mathematical river modeling efforts ever conducted by the Bureau of Reclamation.

The 225 miles of river were modeled with both measured and interpolated cross sections, an assumed Manning's roughness coefficient of 0.035, and three dimensional variation in the initial bed material size gradations. The sediment subteam of the Glen Canyon Environmental Studies agreed that the sensitivity of the following input variables should be tested: (1) bed material grain size distribution and areal extent of the different bed material types, (2) active layer mixing zone thickness, (3) Manning's roughness coefficient (n), and (4) cross section geometry pertaining to the number and shape of interpolated sections.

The purpose of the sensitivity analysis was to determine the relative importance of the STARS model input data in the prediction of sediment transport. This was accomplished by developing a base river simulation and comparing changes in modeled results when input data were varied.

The verification runs made on the Glen Canyon data served as the base runs for determining the sensitivity of the various parameters, except for the distribution of bed material types in the channel. Each of the four parameters was varied and the resulting volume change in streambed analyzed to determine its sensitivity.

Sensitivity analysis was performed on the bed material, active layer thickness, channel roughness, and cross section geometry. Results from the analysis show the STARS model to be most sensitive to the bed material size gradations and least sensitive to the number of cross sections.

Results verify that the STARS model is not oversensitive to variations in input data. For every variable tested, the percentage change in the volume of material removed was less than the percentage change in the input data. The accuracy of the model is within the range of accuracy of the data collection program.

CONCLUSIONS AND RECOMMENDATIONS

The STARS model was developed to mathematically simulate the movement of water and sediment through alluvial river channels. The methods incorporated in the model to compute water surface profiles, determine hydraulic properties by streamtube, calculate sediment transport capacity and supply, route and mix sediment by size fraction, and update cross sections were reviewed in this summary. Specific routines added to route water and sediment where rapids, bedrock outcrops, or side canyon tributaries occur were also discussed. Data collection and required input to the STARS model were summarized, along with the operational concept and the output from the report generator. Results from simulations of the East Fork River and Colorado River from Glen Canyon Dam to Lees Ferry showed the model performed well in the highly variable sand and gravel channel beds and would be applicable to the study reaches in the Grand Canyon.

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RESULTS AND ANALYSIS OF STARS MODELING EFFORTS OF THE COLORADO RIVER IN GRAND CANYON

The Colorado River in the Grand Canyon has a large capacity to store sand along its streambed. Sand supplied by the tributaries will either be carried downstream by the main channel flow or stored on the streambed. Sand that is stored along the streambed is a possible source of material for beach deposition during high flow events. If there is little or no sand stored in the streambed prior to a high flow event, the beaches could experience significant erosion. The Sediment Transport and River Simulation (STARS) model was used to evaluate the relative impacts of powerplant operations on the storage of sand in the main channel. Based on sand material in the streambed and that supplied by tributaries, the STARS model computed changes in sand load transport, channel shape, and bed material size gradation with time throughout the 225-mile reach of river downstream from Lees Ferry.

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INTRODUCTION

Alluvial sand deposits (commonly referred to as beaches) along the Colorado River in the Grand Canyon are a critical resource to recreation, vegetation, and animal habitats. The ultimate source of these sand deposits is the tributaries in the Grand Canyon. Once sand from the tributaries enters the Colorado River it is either temporarily deposited on the streambed or transported downstream. Sand being transported in the main channel of the river can enter eddies or recirculating zones where it may deposit. There could also be a net loss of sediment from a recirculating zone but the stability of alluvial sand deposits is related to sand transport in the main channel. This report documents the relationships of flow releases from Glen Canyon Dam to the sand load transport of the Colorado River's main channel.

A mathematical model was used to quantify the relative impacts of Glen Canyon Dam Powerplant operation scenarios on the Colorado River streambed in Grand Canyon. Results from this study will be combined with other studies concerning rapids, eddy currents, and beaches in order to describe the system of the Colorado River and how it responds to operations at Glen Canyon Dam.

METHODS

MATHEMATICAL MODELING. In order to predict sediment transport of the main channel under various operational scenarios, a mathematical model was required that could handle steep river channels with movable sediments and bedrock. The STARS model, which was developed by the Bureau of Reclamation's Sedimentation and River Hydraulic Section (Orvis and Randle 1987), was selected. The model can be used to mathematically simulate the movement of water and sediment through alluvial river channels and can meet the requirements of the Glen Canyon Environmental Studies (GCES). The unique feature of this one-dimensional, steady-state model is the use of streamtubes (tubes of equal discharge) to vary the hydraulic and sediment transport characteristics across a cross section. This allows for a lateral variation of sediment movement. The model provides information on hydraulic and sediment parameters at each cross section and shows how they change with time. This information includes the amount of scour or fill and rate of sediment transport at each cross section and the net volume of material deposited on or removed from the streambed.

In order to reduce the modeling efforts to a more manageable task, the 240 miles of the Colorado River below Glen Canyon Dam were divided into five reaches:

Reach Number	Reach Boundaries From	To	River Miles
0	Glen Canyon Dam	Lees Ferry	15
1	Lees Ferry	Above Little Colo. R.	61.0
2	Above Little Colo. R.	Near Grand Canyon	26.5
3	Near Grand Canyon	Above National Canyon	78.5
4	Above National Canyon	Above Diamond Creek	59.5

Each reach is bounded by the dam or one of the five sampling stations (Pemberton 1987).

Since the STARS model is one-dimensional, sediment movement within large eddies, such as those observed downstream from rapids or constrictions, cannot be modeled. Many of the popular camping beaches exist downstream of rapids within eddy systems. However, any sediment that is either removed or added to the beaches through eddy currents must be transported at some point by the main channel flow. Integration of the modeling efforts with the work concerning rapids, eddy currents, and beach erosion will more directly address the impacts of Glen Canyon Dam on the beaches along the Colorado River in the Grand Canyon.

STARS MODEL DATA REQUIREMENTS. The data requirements for the STARS model were initial cross section geometry and bed material as well as boundary conditions at the upstream and downstream ends. The downstream boundary condition consisted of water surface elevations varying with time. Upstream boundary information was provided for the main stem and tributaries. This information consisted of discharge, sand supply and size gradation, and water temperature, each varying with time.

The channel geometry for 225 miles of the Colorado River below Lees Ferry was estimated from 708 cross sections. Of these, 209 were measured with sonar and the remainder were interpolated using top widths from low-flow aerial photographs, depths from a depth-profile survey, and side slopes similar to the 209 measured cross sections. The large number of interpolated cross sections were necessary because the model required four cross sections at each rapid in order to compute a reasonable water surface profile. Calibration of the cross section data was performed by vertically adjusting the interpolated cross sections until the model's computed water surface profiles matched well with measured water surface elevations. Measured water surface elevations were obtained from the following sources: The five sampling stations (1983 and 1985-86); the 1923 water surface profile, adjusted for a discharge of 10,000 cubic feet per second (cfs) from observed elevations (Birdseye 1923); the U.S. Geological Survey (USGS) Mapping Service measurements at 15 major rapids; and 1983 high water marks collected in May 1985.

Information on the bed material size gradations was estimated from the channel bottom maps provided by USGS (Wilson 1987). These maps were constructed from side scan sonar charts, low-flow aerial photography, and bed material samples. The maps divide the channel bottom into two major categories: transportable material (sands and gravels) and immovable material (boulders and bedrock). The transportable material is further divided by bed-form: classified as either "sediment wave" or "smooth bottom" patterns. As a first approximation, the "smooth bottom" material is assumed to be coarser than the "sediment wave" material. Bed material samples collected at and between the sampling gages indicate that, in general, the "sediment wave" pattern can be represented as sand and the "smooth bottom" material can be represented as a sand and gravel mixture.

Water discharge hydrographs for five flow alternatives at Glen Canyon Dam were provided by the study manager. These alternatives are described below. The Streamflow Synthesis and Reservoir Regulation (SSARR) model was used to route these flow hydrographs downstream from the dam to determine flow attenuations and travel times (Lazenby 1987).

Sand load-discharge rating curves were developed at each sampling site (Pemberton 1987). These rating curves are necessary for determining the sand load supply at the upstream end of each reach and also as a check on the outflow at the downstream end of a reach. The sand load-discharge rating curves were developed using the Modified Einstein Equation. Total sand load of the Colorado River cannot be directly measured. What can be measured is a load approximately equal to the suspended load. The remaining sediment load or unmeasured load is approximately equal to the bed load. The Modified Einstein Equation computes the total sand load using field measurements of velocity and channel geometry, suspended sediment concentration and corresponding size gradation, and the size gradation of the stream bed material. The sand load is that portion of the total load coarser than 0.0625 mm as determined in the Modified Einstein computations.

Sediment supply from the Paria River, Little Colorado River, and Kanab Creek was also determined from discharge measurements and sediment samples. A suspended sediment rating curve was developed for the period of record for each tributary. The Modified Einstein Equation was applied to a few cases where it was possible to determine the percentage of unmeasured load to the total load. A flow duration analysis, using historical records, was performed to determine the average annual sediment yield. Historical discharge records and a sediment-discharge rating curve were used to determine a typical daily sediment hydrograph for an average year.

The Paria and Little Colorado Rivers together represent 72 percent of the total sand supply from tributaries. Sediment from ungaged tributaries is delivered to the

Colorado River from infrequent floods either by normal channel runoff inflow or debris flows (Howard and Dolan 1981; Webb 1987). Debris flows transport large boulders, but the volume of sand inflow to the river is small relative to the normal tributary sediment yield because debris flow events for a given tributary are rare (approximately 20-30 year recurrence interval). The sediment supply from ungaged tributaries for short-term studies (less than one year) was assumed to be zero. The average volume of sediment supplied from ungaged tributaries from the infrequent floods is small when compared with the average volume of sediment supplied by the Paria River, Little Colorado River, and Kanab Creek, but is important in a long-term study of sediment transport.

MODEL VERIFICATION. Verification of the STARS model on the Colorado River was made using data from cross section surveys conducted in 1956, 1959, and 1965 between Glen Canyon Dam and Lees Ferry. Verification was also made using data collected at the five sampling stations (Lees Ferry, Above Little Colorado River, Near Grand Canyon, Above National Canyon, and Above Diamond Creek) during the period from July to December 1983 and in October 1985. Upon completion of the verification studies, the STARS model was used to predict the relative impacts of Glen Canyon Dam Powerplant operations on the sediment transport in the Colorado River. Comparisons were made of the sediment transport rates, the amount of scour or fill depths, and the volume of material added or removed.

The STARS model has successfully reproduced the degradation of the Colorado River between Glen Canyon Dam and Lees Ferry for the 6.6-year period (2,424 days from February 11, 1959, to September 30, 1965) following closure of the construction cofferdam. The computed change in the bed material size gradation approached an armoring size, and the computed volume of material removed from the 15-mile reach matched the measured volume to within 11 percent (Orvis and Randle 1987).

Discharge, suspended sediment, and bed material samples were collected on the Colorado River at five sampling stations in 1983 and 1985-86. From these measurements, total sand load was computed, and the STARS model was used to simulate the sampling period. For the 1983 sampling period, the model underpredicted the accumulated sand load at the downstream end of Reaches 1 and 2 by 69 and 62 percent, respectively. This might be expected because the initial channel geometry and bed material used as input to the model for the upper reaches represents post-1983 high flow conditions.

After the closure of Glen Canyon Dam in 1963, maximum river flows were relatively low compared with pre-dam flows until the 1983 high flow event. The Colorado River was able to store sand from tributary flows during this 20-year period, but experienced significant scour during the high flows of 1983. The sediment stored on the streambed was the source of sediment which deposited at some beaches in 1983. The sand load computed by the STARS model underpredicted the measured sand load at the gaging station because the initial channel geometry and bed material provided as input to the model represent a degraded channel after a flood.

For the 1985 sampling period, predictions of the STARS model were much better. In this case the initial channel geometry and bed material should more closely match the conditions prior to the verification period. The model overpredicted the accumulated sand load at the downstream end of Reach 1 by 21 percent and underpredicted the accumulated sand load at the downstream end of Reach 2 by 26 percent.

DESCRIPTION OF FLOW ALTERNATIVES. The STARS model was used to simulate sediment transport in the Colorado River under future flow alternatives. Comparison of the river's response to each flow alternative quantifies the relative impacts of the various flow scenarios in terms of sand load transport and sand volume change in the streambed.

Five future flow alternatives were designed by the GCES Study Manager. These flow alternatives represent potential operation scenarios of the Glen Canyon Dam Powerplant. Each scenario provides for the release of the same volume of water in a one-year period (8.25 million acre-feet) in accordance with minimum streamflow requirements and the compact and treaty agreements between Colorado River Basin states and Mexico.

The first alternative represents conditions of steady flow for any given month. In this case, the powerplant would produce a relatively constant supply of electrical energy. The second flow alternative represents conditions of maximum fluctuations (1,000 cfs to 31,500 cfs). In this case, the powerplant would produce a maximum amount of electrical energy during the peak demand and only a minimum amount during low demand. The third flow alternative represents a compromise of the first two flow scenarios (fluctuations from 8,000 cfs to 25,000 cfs). The fourth and fifth flow alternatives were developed with the fishery and recreation studies in mind and are combinations of the first three alternatives. In terms of sediment transport, the first two flow alternatives represent the two extreme powerplant operations. They were the only two alternatives simulated with the STARS model for the upper two river reaches due to time and money constraints and because of small differences in model results for those two alternatives.

River simulations for flow Alternatives 1 and 2 were modeled separately for each of the first two reaches. The input data to the STARS model was the same for each flow alternative with the exception of the discharge and sediment hydrographs at the main stem upstream boundary. The initial channel geometry and bed material input to the STARS model for the flow alternatives was the same as the input for the 1983 and 1985 verification studies. The discharge hydrograph at Glen Canyon Dam was provided by the Study Manager. These discharges were routed downstream with the SSARR model to determine the flow attenuation and travel times of the fluctuating flows (Lazenby 1987). The sediment hydrograph of the main stem was computed from the Modified Einstein sand load-discharge rating curves and the discharge hydrograph.

River simulations for flow Alternative 1 (steady flow) were performed on the first two reaches of river. The first reach was modeled continuously for four years and the second reach for one year. In each case the water year was simulated in 24 major time steps with each time step representing approximately half a month. Although discharges from the dam were constant for a month, inflow of water and sediment from tributaries were allowed to vary twice a month.

Modeling the fluctuating flows of Alternative 2 proved to be much more complex than simulating the steady flow of Alternative 1. Simulating 365 days of flow with approximately 4-hour time steps for the first reach alone would be both time and cost prohibitive. Therefore, modeling one or more years of fluctuating flow required the use of an equivalent steady discharge. To verify the use of an equivalent discharge, two-week simulations of fluctuating flows with time steps averaging four hours were performed for the minimum, mean, and maximum sediment inflow periods. An equivalent steady discharge was determined by trial and error process, which produced the same change in sand storage as the fluctuation flow hydrograph. An equivalent discharge was determined for each month remaining in the water year.

Using equivalent discharges for each month, Alternative 2 was modeled continuously for four years in Reach 1 and one year in Reach 2. Results from the flow simulations of both Reaches 1 and 2 indicate a net fill at the end of a one-year period. This would be expected because the model used initial channel geometry and bed material representing scour after the 1983 high flow event. All of the flow alternatives represent only powerplant releases that are relatively low when compared with the 1983, 1984, or 1985 high flow events.

SEDIMENT MASS BALANCE. The Sediment Transport Analysis Budget (STAB) model was constructed and run as a check on the STARS model and as a tool to analyze sand storage changes for Reaches 3 and 4 and flow Alternative 3 for all reaches. The STAB model computes a mass balance of sand between Glen Canyon Dam and the five sampling stations. Input to the STAB model is the discharge hydrographs at the dam and five sampling stations on the Colorado River, plus discharge hydrographs for the Paria River, Little Colorado River, and Kanab Creek. Sand load-discharge rating curves for each sampling station on the main stem and tributaries are input as well. From this information the STAB model derives a sand load hydrograph for the sampling stations on the main stem and tributaries. From the computed sand inflow and outflow from a reach the change in sand storage was determined for a given release scenario from the dam. Although the STAB model does not account for all the physical processes included in the STARS model, the STAB model was useful for short-term analysis and provided a quick and inexpensive method to evaluate Glen Canyon Dam release patterns.

RESULTS

DEGRADATION FROM HIGH FLOW EVENTS. The STAB model determined 16.2 million tons of sand were removed from the channel between Glen Canyon Dam and the gage Near Grand Canyon (Reaches 0, 1, and 2) during the high flow periods of 1983, 1984, and 1985. Table 1 shows the breakdown by reach and time.

Table 1. STAB model results.

Year	Sand Storage Change (1,000 tons)				
	Reach 0	Reach 1	Reach 2	Reach 3	Reach 4
1983	-2,240	-2,730	-3,270	12	0
1984	-814	-2,950	-1,330	0	0
1985	-580	-2,100	-200	0	0
Total	-3,630	-7,780	-4,800	12	0

COMPARISON OF FLOW ALTERNATIVES. Both the STARS and STAB models predicted aggradation of the streambed upstream from the gage Near Grand Canyon (River Mile [RM] 87.5) for all Glen Canyon Dam Powerplant flow alternatives. This would be expected if it is assumed that the channel had reached a "quasi-equilibrium" (Leopold 1969) prior to the 1983 high flows, and that the river will try to aggrade the streambed until pre-1983 conditions are reestablished. Results from the STARS model are presented in Table 2.

Table 2. STARS model results.

Flow Alternative	Reach	*Sand Storage Change (1,000 tons)			
		Year 1	Year 2	Year 3	Year 4
1	1	629	862	868	786
2	1	515	843	739	699
1	2	1350	-	-	-
2	2	1390	-	-	-

* Typical water year of 8.25 million acre-feet

With the exception of the first year, results from the STARS model indicate that the amount of fill tends to decrease with time because of the model's ability to change both channel geometry and bed material gradation with time. The first year's results from the STARS model indicate a greater amount of transport or less deposition than the subsequent years. This is because initially cross sections with sand-size bed material and high velocities tend to scour until the velocities decrease and the bed material coarsens.

Results from the STAB model are presented in Table 3 and represent an average year in a two- or three-year period.

Table 3. STAB model results.

Flow Alternative	*Sand Storage Change (1,000 tons)				
	Reach 0	Reach 1	Reach 2	Reach 3	Reach 4
1	-28	886	1,330	318	0
2	-78	752	1,140	406	54
3	-49	812	1,240	345	17

* Typical water year of 8.25 million acre-feet.

Results from both the STARS and STAB models indicate the same basic trends. In Reaches 1 and 2, flow Alternative 1 stores the greatest quantity of sand while flow Alternative 2 stores the least. The farther downstream from Glen Canyon Dam, the less difference there is in sand storage between the flow alternatives.

The results from the STAB model for Reaches 3 and 4 do not follow the same trends as those for the upper reaches. This is because the upstream and downstream ends of lower reaches have the same sand load-discharge rating curve and there is some attenuation of peak discharge for flow Alternatives 2 and 3. A large portion of the sand deposition in Reach 3 (318,000 tons) is from Kanab Creek and the rest is caused by attenuation of peak flows.

LONG-TERM PROJECTIONS. The length of time required to resupply sand to the streambed of the Colorado River after a high flow period will vary along the river and will be a function of the quantity of sand supplied by the tributaries. An estimate can be made which assumes an average sediment yield from the tributaries each year and only powerplant releases from Glen Canyon Dam. Both the STARS and STAB models predict a rate of sand deposition in tons/year. To extrapolate past the last computed annual fill rate, future fill rates can be assumed to decrease linearly with time. The time should be determined so that the total quantity of fill is equal to the quantity of sand removed from the 1983, 1984, and 1985 high flow events. Based on these assumptions, the estimated number of years to replenish the streambed with sand to the pre-1983 level is presented in Table 4.

Table 4. Estimated time to establish equilibrium after the 1983 To 1985 high flow periods.

Flow Alternative	Time to Reach Equilibrium (Years)				
	Reach 0	Reach 1	Reach 2	Reach 3	Reach 4
1 (STARS)	-	16	6	-	-
2 (STARS)	-	14	6	-	-
1 (STAB)	infinity	20	7	0	0
2 (STAB)	infinity	17	6	0	0
3 (STAB)	infinity	18	7	0	0

Flow Alternative 2 takes less time to reach equilibrium because it stores the least amount of sediment. The times given in Table 4 are rough approximations and represent only one set of estimates. The actual number of years to reach equilibrium will depend upon the quantity of sand supplied by the tributaries in the years to come.

CONCLUSIONS

The tributaries of the Colorado River in the Grand Canyon are the only source of sediment to the system, since all of the sediments transported by the upper river are trapped in Lake Powell. The long-term average annual sand load from all tributaries in the study reach is estimated at 3.7 million tons/year. The Paria and Little Colorado Rivers together represent 72 percent of this total, and both enter the Colorado River in the reach where there is the greatest potential for erosion of the streambed.

The streambed of the Colorado River has a large capacity to store tributary sand during powerplant operations. The quantity of sand removed from the 102-mile reach between Glen Canyon Dam (RM -15) and the USGS gage Near Grand Canyon (RM 87.5) for the 1983, 1984, and 1985 high flow periods is estimated at 16 million tons. There was relatively little sand removed from the main channel during these high flows downstream from the gage Near Grand Canyon.

High flows (spills) from Glen Canyon Dam, depending upon their frequency, can be much more important to alluvial sand deposits in the Grand Canyon than power-plant operations. The more sand that is stored in the streambed of the Colorado River prior to a high flow event, the greater the potential for deposition of sand at the beaches. For 20 years after the closure of Glen Canyon Dam in 1963, sand storage was maintained in the streambed of the Colorado River. According to Howard and Dolan (1981), alluvial sand deposits in the Grand Canyon began to stabilize in the 1970s. During the 1983 high flow event, there was a net loss of sediment from the study reach, but sediment deposition occurred near many separation zones in the Grand Canyon (Schmidt and Graf 1987). During high flows, sediment previously stored in the streambed is a source of sediment for possible beach deposition. The greater the amount of sand stored in streamed before a high flow event, the greater the potential for beach deposition.

The Colorado River more closely approaches equilibrium with increasing distance downstream from Glen Canyon Dam. This is because the supply of sand to the river increases in the downstream direction due to tributary input and the possible scour of the riverbed upstream. The attenuation of flood peaks in the downstream direction reduces the transport capability. In Reaches 3 and 4, the supply of sand and the transport capability are nearly equal and the channel is near equilibrium.

The operation of Glen Canyon Dam Powerplant impacts the storage potential of sand along the streambed. The greater the sand load transport, the less potential there is for sand storage along the streambed. Although all of the flow alternatives have a similar sand storage potential, Alternative 1 (steady powerplant releases) has the most potential to store sand in the streambed, followed by Alternative 3 (moderate release fluctuations). Flow Alternative 2 (maximum release fluctuations) has the least potential to store sand. The farther downstream from Glen Canyon Dam, the less difference there is between flow alternatives in terms of sand storage potential or sand load transport. This is because of increased sand supply and attenuation of peak flows in the downstream direction.

Fluctuating flows may be more beneficial to alluvial sand deposits (beaches and terrestrial habitat) than steady flows during periods of thunderstorm activity and high tributary runoff (usually occurring from July to October). During this period, the tributaries supply sand to the Colorado River, which in turn provides a source of sand and nutrients to the recirculating zones. Although sustained high river discharges with higher water surface elevations provide the more beneficial sediment inflow to these recirculating zones, the daily fluctuations of discharge with corresponding high water surface elevations will move sediment originating from the tributaries into the beach areas.

In general, beaches are most likely to aggrade if the main channel aggrades during powerplant operations coupled with high tributary inflow. The beaches are most likely to degrade if the main channel degrades during high releases coupled with low tributary inflow. Deposition of some beaches may occur during high flows if the main channel scours and is able to supply sand to the beaches. However, some beaches may degrade during high flow events if the main channel has already degraded in previous high water years.

In the long-term, the frequency of high flow events (greater than powerplant releases) should allow enough time for the main channel streambed to reestablish equilibrium. The amount of time this will take depends upon the volume of sand removed from the streambed and the subsequent sand load supplied by tributaries. The volume of sand removed from the streambed will, in turn, depend upon the water volume and peak discharge of the high flow event. For example, the total discharge from Glen Canyon Dam for water year 1983 was 17,403,000 acre-feet with a peak discharge of 92,600 cfs. If the peak discharge could have been limited to releases of 28,000 cfs that year, then the volume of sand removed and time to reestablish equilibrium would have been reduced by roughly one-third.

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Section IV: Biology Reports

SECTION IV: BIOLOGY REPORTS

* Executive Summaries for GCES Report Numbers 24 and 25 on monitoring bird population densities are not presented in this document.

EFFECTS OF VARIED FLOW REGIMES ON AQUATIC RESOURCES OF GLEN AND GRAND CANYONS

Broad objectives of this study were to: (1) determine distribution, relative abundance, habitat utilization, reproductive periodicity, movement, growth, and food resource utilization by fishes of the Colorado River and its tributaries in Glen and Grand Canyons; (2) determine relative importance of the mainstream and tributaries to life history stages of native and introduced fishes in the study area; (3) assess the relative importance of natural reproduction and artificial propagation (stocking) to maintenance of the trout fishery in the Glen Canyon tailwater; (4) evaluate and predict effects of daily flow fluctuations due to operation of Glen Canyon Dam on native and introduced fishes. This includes direct effects, such as stranding, and indirect effects produced by changes in water quality, habitat availability, and food resources.

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INTRODUCTION

Closure of Glen Canyon Dam in March 1963 marked a dramatic change in discharge patterns in the Colorado River in Glen and Grand Canyons. Prior to closure, there was little daily variation in discharge of the Colorado River in the study area. Rather, variation was seasonal, largely due to increased flows from snowmelt runoff, with occasional summer floods punctuating periods of drought. Since the closure of Glen Canyon Dam, seasonal pulse in discharge from snowmelt has continued, although much abated in most years. Most variation now occurs on a daily basis with dam releases dictated by hydropower needs in the growing metropolitan areas of the southwestern United States.

Impacts of rapidly fluctuating flows on aquatic biota below hydroelectric dams often include reductions in abundances, diversity, and productivity (Petts 1984; Cushman 1985). Organisms adapted to seasonal changes in flow with concomitant alterations of temperature, dissolved oxygen, nutrients, and salinity are imperiled when these changes occur on a daily basis. All trophic levels are affected, directly or indirectly, by these fluctuations, including those of introduced sport fishes and remnants of native fish communities not extirpated by dam emplacement and reservoir impoundment.

METHODS

The Colorado River in Glen and Grand Canyons was divided into five reaches, numbered 10, 20, 30, 40, and 50, by the Arizona Game and Fish Department. The Glen Canyon Environmental Studies, of which this project was a part, numbered the same reaches 1, 2, 3, 4, and 5, respectively. Demarcations of these reaches downstream from the dam were at distances of 15.5, 77, 103.5, 180.5, and 240.5 miles, respectively. In addition to the main stem, eleven perennial tributaries were selected for regular sampling, and several others were sampled sporadically.

Most data were collected during 14 river trips conducted between April 1984 and June 1986. Specific information on the effects of fluctuating flows on fishes was collected during October 1984 and October 1985. The October 1984 investigation emphasized effects on trout in Glen Canyon (Reach 10) and on all species in downriver backwaters. The October 1985 effort was again directed at effects on all species in backwaters of lower reaches. Loss of spawning habitat for trout was monitored directly during fluctuating flows. Effects on trout eggs and alevins were determined by a dewatering experiment at Glen Canyon Dam. A creel survey was conducted at Lees Ferry to determine angling pressure, trout catch rates, and harvest rates, and to collect trout stomachs and heads for food resource and oxytetracycline dye mark analyses. Dye-marked vertebrae of hatchery-reared fish were used to provide information on movement and contribution of natural reproduction to the Lees Ferry fishery.

We measured water quality during most field trips. These observations were supplemented by U.S. Geological Survey (USGS) records and a U.S. Bureau of Reclamation (BOR) simulation model. In order to categorize daily flows according to degree of fluctuation, mean and coefficient of variation (CV) of half-hour measures at the Lees Ferry USGS stage recorder were divided into the following categories:

CV: Low = 0-3 percent, Intermediate = 3.1-15 percent, High = 15.1-100.5 percent

Mean: Low = 3,487-14,000 cfs, Intermediate = 14,001-31,500 cfs, High = 31,501- 51,570 cfs.

Fishes were collected by electroshocking and by various nets suitable for the particular habitat being sampled. Collected fishes were measured, weighed, sexed, assessed for reproductive condition, and, if appropriate, tagged with Floy or Carlin dangler tags. Zooplankton collections were made with the aid of both metered and unmetered plankton nets (see Haury 1987). Benthic algae and macroinvertebrates were sampled both directly (see Usher et al. 1987; Leibfried and Blinn 1987) and as components of fish food resources in the analysis of gut contents.

RESULTS

WATER QUALITY. During the course of this study, mean and coefficient of variation of daily flows at Lees Ferry (15.5 miles below Glen Canyon Dam) varied from 3,487 cfs to 51,570 cfs and 0 percent to 100.5 percent, respectively. Number of days during the study in the nine categories created by the 3 X 3 matrix of these variables was very unevenly distributed with most days falling in intermediate categories of both measures. Days of variable flows falling into the high CV category were restricted almost entirely to the period late autumn to early spring.

Except during periods of flooding when water is released through spillways, discharge through Glen Canyon Dam is drawn from the depths of Lake Powell, more than 60 m at maximum stage. These waters are perennially cold, varying only from 6-12 degrees C, and seldom warming to more than 15.5 degrees C at Diamond Creek, 240 miles downstream. Tributary inflows are generally warmer in summer and colder in winter than the mainstream, but their combined discharge is insufficient to affect the temperature of the Colorado River.

Major ion proportions in the Colorado River were of the order: Ca > Na > Mg > K; and SO_4 > HCO_3 > Cl. Tributaries varied from dilute dolomitic waters with high proportions of Ca, Mg, and HCO_3 to saline sodium chloride waters, but their combined effect produced only a slight increase of Na and Cl proportions in the mainstream during this study. In like manner, mean conductivity values increased only from 709 μS to 744 μS between the upper and lower reaches of the study area.

Mean mainstream NO_3-NO_2 concentrations varied between 315 μg/l and 350 μg/l with no apparent downstream trend. Tributaries were variable with means of 13-759 μg/l. Ammonia levels were generally <5 percent those of NO_3-NO_2 in the Colorado River and its tributaries. Soluble reactive phosphate and total phosphate mean concentrations exhibited a downstream increase in the mainstream. Mean values ranged from 11.0 μg/l to 171.5 μg/l for the former and 15.8-290.9 μg/l for the latter. Observed increases were attributable largely to inputs from the Paria and Little Colorado Rivers, both of which contain waters high in suspended clays and adsorbed phosphorus when in flood.

Molar N/P ratios in the Colorado River suggest that this system, if nutrient limited in primary productivity, is limited by phosphorus. Such limitations may not occur frequently, except perhaps in the reach above the Little Colorado River (LCR). Below the LCR, dissolved phosphate concentrations increase, but this increase is accompanied by considerable reduction in light penetration during part of the year, due largely to turbidity imparted to the mainstream by suspended sediments in runoff of the LCR.

FISH DISTRIBUTION AND ABUNDANCE. The fish community of the Colorado River below Glen Canyon Dam has changed from one composed of endemic and warm-water species prior to and soon after closure of the dam to a community dominated by introduced, cold-water and eurythermal species. Although some native species have persisted through the changing environment, several have been extirpated, including Colorado squawfish, bonytail chub, roundtail chub, and, possibly, razorback sucker. Introduced warm-water species such as red shiner, black bullhead, channel catfish, green sunfish, bluegill, and largemouth bass have either disappeared or decreased in abundance. Rainbow and brown trout have increased due to stocking, introduction of suitable food resources, and the transition to a favorable, cold-water environment provided by the deep, hypolimnial release waters from Lake Powell.

Four species of introduced trout (rainbow, brook, brown, and cutthroat) were collected from the study area, but the last was taken very infrequently. The remaining three species had overlapping, but disparate, downstream distributions. Rainbow trout were collected throughout the study area, although electrofishing catch rates were highest from the dam to Lees Ferry (Reach 10). Annual stockings of fingerling rainbow trout and the relatively high abundance of aquatic invertebrates and other food items (Leibfried and Blinn 1987) probably contributed to higher catch rates in this reach. Electrofishing catch per unit effort

(CPUE) was highest in runs above the LCR where waters were relatively clear, whereas highest catch rates occurred in backwaters below the LCR. All tributaries sampled produced individuals of this species, although relatively high gradient, clear-water streams fed by springs contained higher densities. Rainbow trout fry selected habitats with low or no current.

Brown trout abundance seems to have increased since the investigation of Carothers et al. (1981). The species is largely restricted to the mainstream and tributaries in Reaches 30 and 40, with highest concentrations above and below the confluence of Bright Angel Creek. Unlike rainbow trout, brown trout were often caught in areas without vegetation, a possible reflection of their more piscivorous nature.

Brook trout abundance declined with distance downriver, with very few individuals taken below Reach 20 or in tributaries. Distribution appeared to be controlled by water temperature, stocking location, and capacity to disperse downriver, because no evidence of natural reproduction was observed during this study. It appeared that brook trout and rainbow trout used different habitats in the mainstream.

The other common introduced species, common carp and fathead minnow, were most abundant in lower reaches of the river. Carp preferred habitats with slower water velocity, but did not seem to select any one substrate type. Carp distribution and abundance may be regulated more by water temperature and velocity than habitat type. Fathead minnow densities were highest along runs with emergent vegetation. Vegetation served to diminish current velocity and probably provided substrate for food resources.

Adult and larval bluehead sucker were most abundant in lower reaches. The higher velocity runs and side channels and rubble substrate selected by adult bluehead sucker are probably feeding areas for these scrapers. Larval bluehead sucker were generally collected in shallow backwaters.

Unlike other native fishes, adult flannelmouth suckers were most abundant in Reach 10. Juvenile and larval stages were most common in the lower reaches, and were never collected in Reach 10. The lower portion of the river serves as an important nursery and rearing area for this species; then, as these fish grow, they disperse throughout the river. Backwaters, where flannelmouth sucker catch was greatest, may be feeding, resting, and spawning habitats for this species. Like other larval natives, flannelmouth sucker larvae were generally in lentic, sand or silt-bottomed backwaters.

Speckled dace were collected from a variety of mainstream habitats, but seemed to be concentrated in backwaters and side channels of lower reaches where waters were warmer than the main channel. This species was collected from all mainstream reaches and from nine of the eleven regularly sampled tributaries.

Adult humpback chub were collected in Reaches 20-50, but most individuals were captured in the proximity of the LCR. Most young-of-the-year (y-o-y) and subadult humpback chub were collected from Reaches 30 and 50, where most backwaters occur. Adult and subadult humpback chub generally were collected along cliffs and boulders in the main channel. Vegetation did not appear to be important in habitat selection. Y-o-y chubs were captured in sandy run and backwater habitats similar to those reported in the Upper Basin (Holden 1978; Valdez and Clemmer 1982).

Upper Colorado River Basin backwaters are important nursery and rearing areas for both native and introduced fishes (Valdez et al. 1986). Backwaters in our study area appeared to be very important to fishes for these purposes, mainly during the period of spring through early autumn. When backwaters cooled to near or below main channel water temperatures, fish abundance decreased. As found in the Upper Basin (Valdez et al. 1986), introduced fishes were generally the most abundant group in backwaters. Fathead minnow, which thrive in pond environments, were very common.

Colorado River tributaries in Grand Canyon also serve as important habitats for both introduced and native fishes. Seasonal use of tributaries by different species is reflective of water temperature changes, with trout most abundant in winter (December-February) and native species predominant in spring and summer (March-August).

FISH REPRODUCTION. Unlike rainbow trout, neither brown nor brook trout appeared to reproduce successfully in the Colorado River. Only rainbow and brown trout showed evidence of successful reproduction in tributaries. Brook trout reached reproductive condition only in the mainstream, and no fry were collected.

Carp and fathead minnow reproduction appeared to occur only in backwaters. A minimum temperature of 16 degrees C is required for both species to initiate spawning (Swee and McCrimmon 1966; Carlander 1969). Thus, main channel temperatures inhibit spawning, and this activity is restricted to warmer backwaters.

Native suckers utilized both the main channel and tributaries for spawning and nursery areas. Presence of larval bluehead suckers above the confluence of the Paria River in Reach 10 suggests that ova can develop and hatch in the cold tailwater. However, these larvae were dead, and, therefore, recruitment is in question. Most larval bluehead sucker were collected from backwaters in lower reaches.

Flannelmouth sucker in ripe condition were collected throughout the year from the study area, although the peak in reproductive condition occurred in spring. Concentrations of fish in reproductive condition were often found at the mouths of tributaries and in connected backwaters. Individuals in reproductive condition were found in all mainstream reaches, but larvae were collected only in Reaches 40 and 50. Ripe females were taken from five of the eleven regularly sampled tributaries.

In the Grand Canyon, humpback chub spawning is apparently restricted to the LCR during the period March-June in water temperatures of 16-20 degrees C (Suttkus and Clemmer 1977; Minckley et al. 1981; Carothers and Minckley 1981; Kaeding and Zimmerman 1983). No spawning sites or larval humpback chub were found in the main channel during our study. Water temperatures there may not be warm enough to initiate spawning. If spawning were to occur in the main channel, egg and larval mortality would greatly diminish any chance for recruitment. Y-o-y chub were collected in lower reaches of the river, suggesting that either spawning areas other than the LCR are present, or that young chubs are transported or swim from this tributary into the mainstream.

EFFECTS OF FLUCTUATING FLOWS. During the period 19-21 October, 1984, when discharge was decreased from 23,000 cfs to 5,000 cfs in eight hours, more than 800 rainbow trout were observed stranded in the Lees Ferry area. Mortality was high among these fish, up to 95.2 percent in one pool, even though water temperature in isolated pools did not increase more than 2-3 degrees C above that of the mainstream.

Variation in water flow has been shown to affect trout spawning (Anderson and Nehring 1985) and may have been responsible for a temporal shift in Reach 10 reproductive activity observed during this study. Flows during winter 1984/85 were steady and high enough to maintain trout access to spawning bars. During winter 1985/86 fluctuating flows, access to spawning bars, and some downstream tributaries was restricted. Peak spawning activity did not occur until spring when steady flows returned. This temporal shift was evident in the Reach 10 creel where most fish were in reproductive condition during winter 1984/85, but did not reach that condition until spring in 1986.

Emergence of rainbow trout fry from simulated natural redds in raceways below Glen Canyon Dam varied dramatically between steady flow and dewatered conditions. In the steady flow raceway, 12 percent of planted eggs produced emergent fry, whereas in the raceway dewatered daily for 10 hours, only 0.6 percent produced fry.

Rainbow trout was the only species to exhibit a statistically significant decrease in CPUE in backwaters during fluctuating flows of October 1985 (ANOVA, $P < .005$). CPUE of fathead minnows also decreased, with those caught being smaller, as was the case for most introduced species. Larger individuals, being more mobile, may have moved more readily to other areas less affected by changing water levels.

Of native fishes, flannelmouth sucker and speckled dace in backwaters generally showed a decline in CPUE and relative abundance during these fluctuating flows. Bluehead sucker seemed to increase, and humpback chub exhibited different responses among reaches.

MOVEMENT. Data were collected for three native species (flannelmouth sucker, bluehead sucker, and humpback chub) and four introduced species (rainbow trout, brown trout, brook trout, and carp). Most tagged and recaptured fish (641/14,760) were rainbow trout. Despite low tag returns for the remaining six species, several movement trends were evident. Movement into and out of tributaries during spawning season was observed for rainbow trout, brown trout, flannelmouth sucker, and humpback chub. Six of 41 humpback chub recaptures were individuals that had moved from the LCR to mainstream Reaches 20 or 30.

Main channel movement was predominantly downstream, although humpback chub recaptures tended to be upstream. Mean distance moved varied from 0.3 mile (humpback chub) to 10.1 miles (flannelmouth sucker). Low mean distance moved in humpback chub was due to most individuals being tagged and recaptured within the LCR. The longest time to recapture for humpback chub was for an individual tagged on August 13, 1978, an interval of 2,477 days. This fish had grown only 11 mm since being tagged.

Oxytetracycline dye-marked rainbow trout were stocked at Lees Ferry from October 1983 to April 1986. Dye-marked trout comprised 61 percent of the sampled fish in Reach 10. Only 7 percent were dye-marked in Reach 20, and this percentage declined steadily to 0 in Reach 50. Natural reproduction is known to occur because unmarked fish smaller than stocked individuals (<100 mm) were sampled in the Lees Ferry area. Contribution to the creel from natural reproduction was estimated at 27 percent. Most fluctuating flows occurred late in the study, so there was little opportunity to document their effects on fish movement. However, movement by several fish species to or from tributaries during spawning season was observed to be impeded by fluctuating or low flows.

FISH FOOD RESOURCES. Food resource utilization of fishes was examined by analyzing gut contents in bluehead and flannelmouth sucker fry, and in rainbow trout fry and adults. Immature chironomids were numerically predominant in fry guts of all three species. Zooplankton, primarily copepods and cladocerans, was of second highest proportion in flannelmouth sucker and mainstream rainbow trout fry, but other immature insects held this position in bluehead sucker fry. Proportion of zooplankton declined dramatically in rainbow trout fry collected below Reach 10.

Adult rainbow trout guts had high volumetric proportions of the filamentous green alga <u>Cladophora glomerata</u>, immature insects (mainly chironomids and simuliids), or the amphipod <u>Gammarus</u> <u>lacustris</u>, depending upon stream reach. Proportions of these major food groups also varied on a seasonal basis. <u>Cladophora</u> amounts were greatest in summer and lowest in winter; <u>Gammarus</u> and immature insect proportions changed in a manner opposite to that of the green alga. Relative amount of the amphipod in rainbow trout guts increased dramatically during a three-day period when dam releases were decreased deliberately. This suggests that the amphipod's susceptibility to trout predation can be affected by operations of Glen Canyon Dam.

AGE AND GROWTH. Length frequency distributions were used to estimate growth of fish because it was not possible to age them by conventional scale and otolith methods. Growth rate of rainbow trout was highest in upper reaches of the Colorado River and decreased below the confluence of the Little Colorado River. Condition factors for rainbow trout also decreased with distance downstream from Glen Canyon Dam.

First year growth of humpback chub was estimated to be 70 mm. Growth of adults (>250 mm) was estimated to be approximately 10 mm/yr. First year growth of bluehead and flannelmouth sucker was estimated to be approximately 70-100 mm. Growth of adult suckers was variable but generally slow.

LEES FERRY FISHERY. Our creel survey and those previously conducted at Lees Ferry showed that fishing pressure increased greatly from 1977 to 1983 and then decreased greatly. Catch rates for trout increased from 1977 to 1985 and then decreased in 1986, probably due to a change in regulations which prohibited the use of bait.

Mean length of creeled rainbow trout decreased from 1977 to 1985, probably due to lack of stocking from April 1978 to August 1980 and higher angler harvest. Mean lengths increased in 1986 despite the fact that few large fish were checked at the creel station. This was because very few small rainbow trout were kept by lure and fly-only fishermen. Brook trout were not stocked from November 1983 to August 1985, and their numbers and harvest rate decreased during each year of the study.

There were significant seasonal differences in catch rates for all trout species combined and significant seasonal differences in mean lengths and condition factors for rainbow trout (ANOVA, $P < .05$). Catch rates and mean lengths were greatest during winter, coinciding with the rainbow trout spawn. Mean condition factors were lowest during winter.

Daily catch rates varied significantly among daily mean flow categories (ANOVA, $P < .05$). Catch rates were highest when mean daily flows were less than 14,000 cfs. Daily catch rates also varied significantly with discharge categories (ANOVA, $P < .05$), which included effects of both mean and coefficient of variation of daily flow.

DISCUSSION

The biota of the Colorado River in Glen and Grand Canyons evolved in a system with wide seasonal fluctuations in water temperature and volume (Dolan et al. 1974; Cole and Kubly 1977; Turner and Karpiscak 1980). Closure of Glen Canyon Dam and subsequent withdrawal of deep hypolimnial waters from Lake Powell has changed downriver temperatures. Pre-dam seasonal temperature variations of 12 degrees C have been replaced by near constant temperatures that increase only 5 degrees C in flowing 240 miles downstream. Pre-dam seasonal discharge patterns, characterized by spring floods from snowmelt, also have been largely eliminated. Only in recent years of high inflow to Lake Powell have spring releases approached pre-dam flows.

Decreased water temperature has been strongly implicated as a primary cause for extirpation of native fishes from regulated portions of the Colorado River (Vanicek et al. 1970; Holden and Stalnaker 1975; Behnke and Benson 1980). Loss of spring floods and seasonal warming in Colorado River waters have removed two key environmental cues used by fishes and other aquatic organisms as signals for gonadal maturation and the onset of reproductive activity. Furthermore, growth rates in these poikilotherms are generally temperature dependent, and, thus, time of reproductive maturity or size at reproductive maturity probably are affected in all but cold-water species.

The endangered humpback chub in the Colorado River above Lake Powell reproduce in mainstream habitats (Archer et al. 1985), but no chub larvae were found outside the LCR in Grand Canyon. Main channel water temperatures were at or near levels lethal to humpback chub ova (Hamman 1982) and were well below the optimum for y-o-y individuals (21-24 degrees C) (Bulkley et al. 1981). Restriction of humpback chub reproduction to the LCR, however, suggests that factors other than temperature prevent successful reproduction in other tributaries having similar thermal regimes.

In contrast to humpback chub and previously extirpated native fishes, the cold, clear waters released through Glen Canyon Dam provide a favorable environment for introduced trout. Mainstream water temperatures of 10-15 degrees C coincide with those preferred for spawning by rainbow trout, the most common species (Scott and Crossman 1973), and increased water clarity allows high productivity of Cladophora, epiphytic diatoms, and invertebrates that form the food base of these fishes (Leibfried and Blinn 1987).

Daily flow fluctuations in the Colorado River below Glen Canyon Dam often produce stage (water surface level) changes of over 1.5 m, in contrast to only several decimeters prior to impoundment. Even greater water level fluctuations are evidenced on weekends and holidays (Turner and Karpiscak 1980). Fluctuations of this magnitude cause marked instability of inshore, shallow-water, low-velocity habitats used extensively by fishes for resting, feeding, spawning, and nursery areas. Subsequent dewatering results in stranding, exposure, and desiccation of both fishes and their food resources.

Persons et al. (1985) showed that as discharge from Glen Canyon Dam fluctuates, areas of inshore habitat suitable for trout fry are displaced, forcing these individuals to enter higher-velocity waters in search of new sites. Thus, fry could theoretically be displaced downstream with each cycle of flow fluctuations.

Similar effects can be predicted for early life stages of native fishes in downstream backwaters. Fluctuating flows dewater backwaters, either stranding fishes or forcing them into cold, main channel waters. When fluctuations occur in autumn, as they did during the present study, effects are minimized because immature native fishes have already grown beyond the larval stage. Our backwater results could have been much different if fluctuating flows had occurred during summer when larvae of many species are common in backwaters. Larval fish have much less mobility, and, thus, could be forced downstream with each daily cycle in flow. Each movement would subject these individuals to mortality from river currents, thermal shock, predation, or starvation. This could result in individuals surviving only in habitats less affected by changing flow levels.

Based on video habitat analysis at 4,800 cfs and 28,000 cfs (Anderson et al. 1987), there was a decline in absolute numbers of backwaters at the higher flow, and many backwaters disappeared while new ones were formed in the transition between the two flows. Holden (1978) found that preferred habitat for y-o-y humpback chub was connected backwaters with little current and a maximum depth of 2 ft (0.6 m). In the reach immediately below the LCR, a 2-foot drop in water elevation was common during the fluctuating flows of October 1985.

CONCLUSIONS

Impoundment of the Colorado River by Glen Canyon Dam and release of cold, hypolimnial water from Lake Powell has dramatically changed the physicochemical and trophic nature of the river downstream. The thermal regime produced by these release waters persists with little change for a distance of 240 miles despite inflows from numerous small tributaries. Of these tributaries, the LCR most affects other physicochemical characteristics of the mainstream.

The post-impoundment native fish community in Grand Canyon has suffered the extirpation of three, possibly four, species. Remaining natives have contracted distributions, particularly in loss of reproductive habitat for adults and rearing areas for larval and juvenile fishes. Reproduction by endangered humpback chub was observed in only a single tributary, the LCR. This stream and most remaining perennial tributaries are used as spawning and rearing sites by other native fishes.

Fluctuating flows were observed to cause increased mortality and decreased reproduction through stranding, exposure to terrestrial predators, loss of spawning habitat, and loss of larval and y-o-y habitat. These flows impacted both native and introduced sport fishes.

Backwater habitats are important spawning and rearing areas for both native and introduced fishes. Y-o-y humpback chub from the LCR apparently use downstream backwaters as feeding and resting areas until they reach sufficient size to survive in the main channel. Fluctuating flows produce instability in backwater habitats, forcing fishes to return to the main channel, or, if they are stranded, subjecting them to exposure, desiccation, and predation.

Cold, clear hypolimnial release waters from Glen Canyon Dam provide a favorable environment for trout and their food resources (e.g., *Cladophora*, amphipods, and chironomids) in the tailwater. Extreme fluctuating flows make more of these resources available to trout as drift, but such fluctuations are deleterious to spawning trout, alevins, and fry.

RECOMMENDATIONS

High, steady spring and summer flows could benefit humpback chub spawning and larval chub survival in the LCR. High water levels in the mouth of the LCR during this period create a lentic environment which may serve as a staging area for reproductively active humpback chub adults and as a zone of thermal acclimation for young chub entering cold main channel waters. Steady flows would also contribute to the stability of backwater environments used as rearing areas for y-o-y chub and other fishes, and would allow plankton and benthos populations to increase and provide food resources to resident fishes. Steady flows during winter and spring should benefit trout spawning, alevin survival, and maintenance of stable fry habitat.

Very high flows (powerplant capacity and above) mimic that of the pre-dam period and may provide some benefit to native fishes. Desert river fishes have evolved in systems characterized by flood-drought cycles, and we anticipate that they will survive extreme high flows better than most introduced species. The rate at which flows were increased and subsequently decreased would be an important factor determining effects on both native and introduced fishes.

A potential problem associated with bypassing the powerplant is the introduction of new species from Lake Powell and upper reaches of the Colorado River or its tributaries. Introduction of new species, or even additional individuals of certain species now rare in Glen and Grand Canyons, could have deleterious effects on important native and introduced sport fishes inhabiting this reach.

High, continuous fluctuations would have negative impacts on most aquatic resources. Gravel bars used by trout as spawning sites would be dewatered daily, resulting in the stranding of adult spawners and mortality of eggs and alevins in dewatered redds. Emergent fry would be stranded or displaced from nearshore habitats on a daily basis. Low flows would limit spawning fishes access to some tributaries.

Native fishes would be similarly impacted by dewatering of main channel spawning habitats. Backwaters that provide warm-water habitats for larval native fishes would be sequentially dewatered and refilled with cold main channel water. Stranding, flushing, and alteration of thermal regimes would also negatively impact invertebrate populations that serve as fish food resources.

Extreme fluctuating flows during May and June might negatively affect the success of humpback chub spawning and increase mortality of larval chubs. Adults would not have the advantage of a stable, pooled area in the mouth of the LCR as a reproductive staging area, and larval chub might be flushed daily from the lower reaches of this tributary into cold main channel waters.

A limited amount of fluctuation might be necessary, however, to replenish nutrients necessary to maintain growth of these food resource populations, and to increase drift (hence, availability) of food organisms for trout.

Future drought years, coupled with continued demands for hydroelectric power and legal requirements for retention of water in Lake Powell, may well provide our greatest challenge for the maintenance and well-being of aquatic resources in Glen and Grand Canyons. To best benefit aquatic resources under these conditions, we feel that fluctuating flows should be minimized, and low flows restricted to late autumn and winter to conserve water for native fish spawning and rearing in spring and summer. Increased stocking of trout might serve to mitigate losses from natural reproduction under winter low flows, but we are unsure what population levels could be supported in the reduced habitat space.

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COLORADO RIVER WATER TEMPERATURE MODELING BELOW GLEN CANYON DAM

This study presents an analysis of Colorado River temperature modeling below Glen Canyon Dam, Arizona. The potential of raising the water release temperatures at the dam by modifying dam penstocks with multiple-level intake structures is discussed. Predicted temperatures of waters drawn from Lake Powell by such intake structures are calculated with a computer model for both four and eight modified penstocks. The temperature change of this warmer water as it moves downstream through the Grand Canyon is then evaluated using both a computer-generated temperature function and a simplified graphical method.

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INTRODUCTION

Prior to completion of Glen Canyon Dam, the Colorado River temperature seasonally ranged from 32.4 degrees Fahrenheit (F) to 82.4 degrees F (1949-1962). Since the completion of the dam, the seasonal temperatures have decreased and now range between 41.9 degrees F to 64.4 degrees F (1962-1976) (Turner and Karpiscak 1980). The river water temperature at the Lees Ferry gaging station for the months of May through October 1977-83 averages around 50 degrees F.

The cooling of Colorado River water adversely affected the native fish in the Grand Canyon, but it created a trophy trout fishery below the dam. On May 25, 1978, the U.S. Fish and Wildlife Service (FWS) issued a Biological Opinion that stated that the dam was "jeopardizing the continued existence of the humpback chub and is limiting and rendering unsuitable the recovery of a reach of the Colorado River known to support Colorado River squawfish" (U.S. Fish and Wildlife Service 1978). The FWS presented four reasonable and prudent recommendations that would work toward remedying the situation. Two of the four recommendations directly concerned the thermal conditions of the river in the Grand Canyon:

(1) Study the impact of warming releases from Glen Canyon Dam.

(2) Reduce or eliminate known constraining factors of low temperatures and frequent flow fluctuations.

Prior to addressing the impact of warming the releases from the dam, it was necessary to determine if the release temperatures could be raised and, if so, how the thermal conditions throughout the Grand Canyon would be modified. This study was a preliminary effort to address these questions.

Water can be released from Glen Canyon Dam three ways: through powerplant generators, through river outlet tubes, and through spillways. Both of the latter means bypass the powerplant. Since the primary operating objectives of the dam are water storage and power generation, the majority of water is and will continue to be routed through the powerplant. Bypassing the generators (spilling water) is avoided if possible. The U.S. Bureau of Reclamation manages releases from the dam in order to maintain a water level in Lake Powell that will always be above the minimum power elevation of 3,490 ft. The dam has eight generators, each fed by a 15-ft diameter penstock tube that draws water from the upstream side of the dam, passes it through the generators, and discharges it downstream in the Glen Canyon Dam tailwater (Figure 1a-b). The penstock intakes are at 3,470 ft. The decision to place the intakes at this elevation was based on predicted reservoir operations and the amount of head (reservoir height) required to efficiently operate the generators. The generator discharge is at 3,140 ft; consequently, the water drops 330 ft from the penstock intakes. The surface elevation of Lake Powell seasonally varies, depending on anticipated and actual runoff from the Upper Colorado River Basin. Since the filling of Lake Powell in 1980, the surface elevation has ranged from approximately 3,670 ft to a full reservoir of 3,700 ft. Therefore, the depth to the penstock intakes during this time period has varied from 200 to 230 ft below the surface of the lake. Each penstock is surrounded by a trashrack structure that prevents debris from being drawn into the turbines and causing damage.

The hydrologic and limnological characteristics of Lake Powell have been discussed in detail by Merrit and Johnson (1977), Reynolds and Johnson (1974), and Edinger and Buchak (1982). They found the lake meromictic (a lake with incomplete circulation), but with a strong, warm monomictic (a warm-water lake turning over once per year) thermal circulation in the upper 230 ft. The seasonal longitudinal and vertical

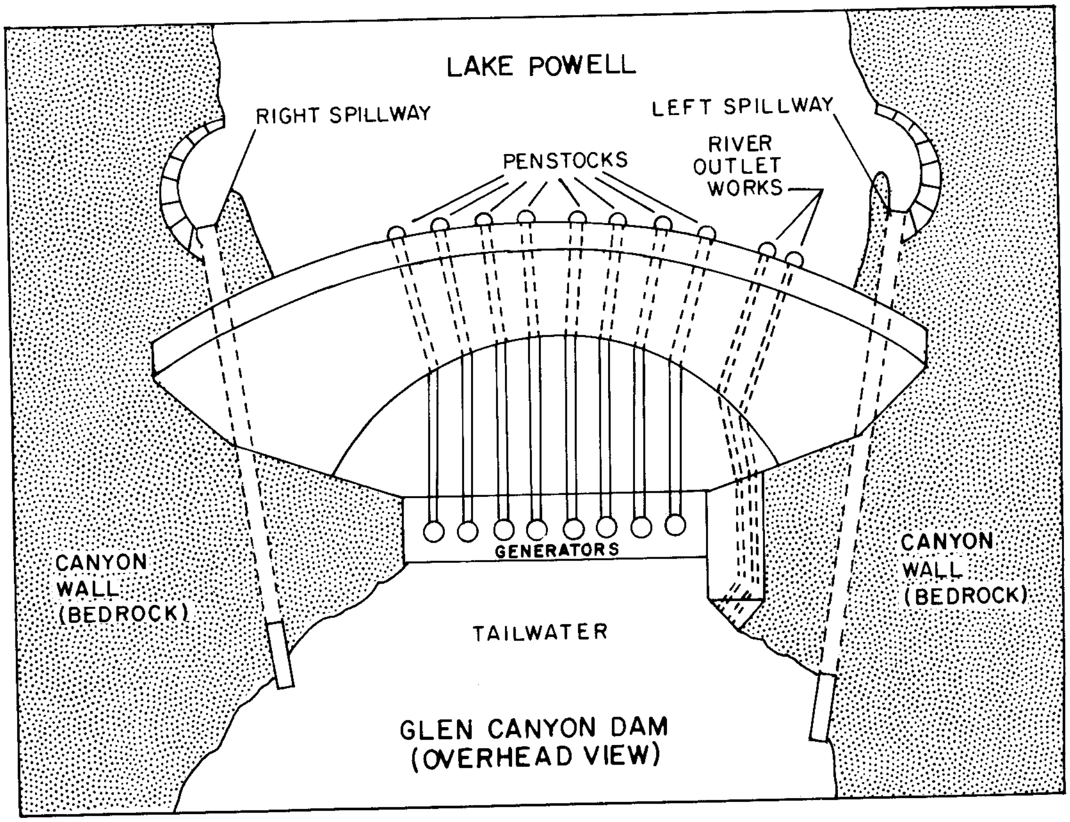

Figure 1a. Overhead view of Glen Canyon Dam.

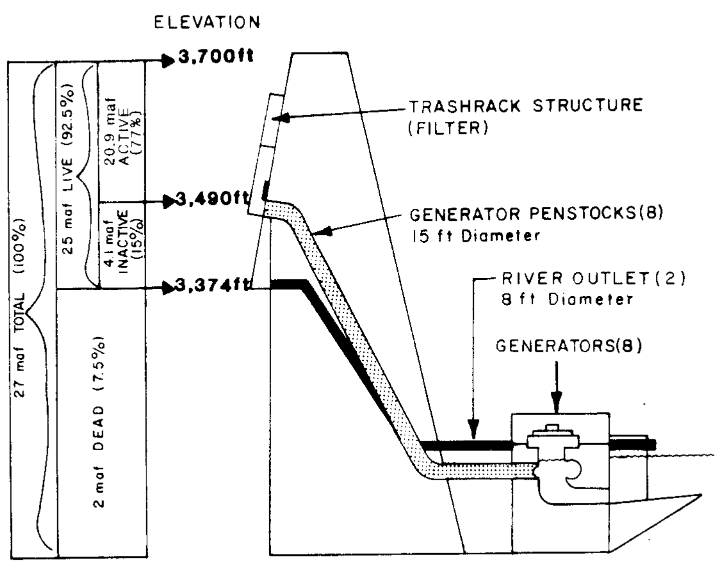

Figure 1b. Side view of Glen Canyon Dam.

temperature structure is defined by inflow densities, heat exchange, and fall overturn. During the summer months, an epilimnion with a depth of 23-50 ft is typically developed. An epilimnion is the upper layer of warm water in the lake containing more oxygen than the lower layers. Summer surface temperatures have reached 79 degrees F. A strong thermocline, ranging in thickness from 30-50 ft, seasonally forms below the warm epilimnion. The thermocline is the layer of water between the warmer surface zone and the colder deep-water zone. From the bottom of the thermocline to the lake bed, the temperatures are isothermal and vary between 43 and 45 degrees F. The epilimnion and thermocline typically turn over each fall as ambient air temperatures decrease.

Based on these reservoir characteristics, and level of penstock intakes, the water drawn through the dam is consistently from the isothermal zone of the reservoir, with occasional seasonal withdrawals from the bottom of the thermocline region. Consequently, the temperature of water drawn into the dam is dependent on the lake elevation. For example, on September 14, 1982, the lake elevation was at 3,685 ft, so the penstocks drew water from 215 ft below the lake surface at a temperature of 47 degrees F.

The temperature of water released from the dam could be increased by withdrawing water from a warmer level of the reservoir. This would be accomplished by attaching to the existing penstock intakes temperature control structures that would allow withdrawal of water from various levels nearer the surface of the lake. Such a modification was made in 1978 to Flaming Gorge Dam in Utah (Schmidt et al. 1980). At that facility, multiple-level intake structures were fabricated and retrofitted to the upstream face of Flaming Gorge Dam by hard hat divers. Similar multiple-level intake structures could be developed for Glen Canyon Dam.

The proposed structure, featuring a series of vertically stacked shutters (or gates), would enclose each penstock intake. Different configurations of gates could be opened to vary the withdrawal level. Gate control would be automated, and adjustments would be made in relation to reservoir elevation, turbine operation, and water temperature.

METHODS

In order to assess the results of modifying the penstocks at Glen Canyon Dam, two separate modeling evaluations were made. The first was designed to project the temperatures of waters released from dam outlets for different possible gate elevation schemes for the proposed multiple-level intake structures, and the second, to predict the increase in temperature as the river water flows downstream through the Grand Canyon.

Before initiating the study, an analysis was made of available models, the data required for these models, and the data available for Lake Powell and the Colorado River. The reservoir outlet temperature model chosen was BSelect2, a withdrawal allocation sub-routine similar to the withdrawal portion of the U.S. Army Corps of Engineers Water Quality for River-Reservoir Systems (WQRRS) model (U.S. Army Corps of Engineers 1978). Using just the withdrawal portion provides an easier and quicker method for entering the data and obtaining the results. The model was adapted to reflect the thermal conditions that would be available at the selected multiple-level intake gate elevations.

Two river temperature models were selected to analyze the routing of the powerplant releases through the Grand Canyon: (1) "A Graphical Technique for River Water Temperature Predictions" (Graphical) (Krajewski et al. 1982), a model based on the average equilibrium temperature method; and (2) the "Stream Quality Model, Qual-II" (Qual-II), developed by the U.S. Environmental Protection Agency (1977; Roesner et al. 1977a-b). These relatively simple models were chosen because of the limited Grand Canyon climatological and river water temperature data available and the level of output needed for this study.

Very little atmospheric data have been collected in the Grand Canyon, except for long-term temperature and precipitation statistics collected at the National Weather Service (NWS) Phantom Ranch weather station, located in the central part of the canyon. In 1983, the NWS started collecting temperature, relative humidity, wind speed, and precipitation data at the Tonto Rim weather station, located near Phantom Ranch approximately 1,000 feet above the river.

Many years of pre- and post-Glen Canyon Dam daily Colorado River water temperature records (Table 1) are available from the U.S. Geological Survey (USGS)

(1980) for the Colorado River At Lees Ferry gaging station (located 15 river miles below Glen Canyon Dam) and at the Near Grand Canyon gaging station (located near Phantom Ranch, 100 river miles below the dam).

Table 1. Pre-dam and post-dam average monthly Colorado River Temperature (degrees F) for Lees Ferry and Near Grand Canyon gaging stations.

	Pre-dam			Post-dam	
Month	Lees Ferry 1953	Near Grand Canyon 1953	Near Grand Canyon 1952-1962	Lees Ferry 1977-1983	Near Grand Canyon 1970-1976
May	61.5	61.5	64.5	49.0	51.5
Jun	68.0	69.0	71.5	49.5	53.5
Jul	80.5	79.0	78.0	50.0	54.5
Aug	79.0	77.0	78.0	49.5	55.5
Sep	75.0	73.5	73.0	50.5	55.0
Oct	-	62.0	62.0	50.0	54.0

River temperature data were collected during the water years 1952-53 (pre-dam) and 1977-1983 (post-dam) at the Lees Ferry station and during 1940-1976 and part of 1983 at the Grand Canyon station. The 1952-53 water year was the only period for which daily pre-dam river water temperatures were obtained from both sites.

OUTLET TEMPERATURE MODELING (BSelect2). The BSelect2 model was calibrated using reservoir water temperature data collected near the dam at Wahweap Bay by the U.S. Bureau of Reclamation. These data have been collected, usually six to eight times per year, since the closure of the dam. The water temperature is measured at the reservoir water surface and at 50-ft intervals to the bottom elevations of 3,200 and 3,190 ft.

Release temperatures were calculated for two scenarios: with temperature control multiple-level intake structures installed on (1) all eight of Glen Canyon Dam's penstock intakes, and (2) just four of the intakes. While both options were investigated, temperature control structures would be needed on all of the dam's intakes, both to attain maximum temperature increase when all eight intakes were in use for high power production, and to retain the flexibility of choosing which turbines (i.e., penstock intakes) to use during times of lower power production. The dam is regularly used for peaking power generation, Which means all eight intakes are used on a variable but regular basis.

In the model, gate elevations on the proposed temperature control structures were arranged after examining the last 10 years of reservoir water surface fluctuation records and assuming some structure limitations. Two different gate configurations were selected so that consistent release temperatures could be maintained for the different reservoir elevations occurring from year to year. It was assumed that the highest gates on the structure would need to be 30 ft or more below the reservoir water surface to avoid developing a vortex on the reservoir surface near the dam. Since the completion of the analysis, it has been suggested that 30 ft may have to be increased to 45 ft, resulting in a slight decrease in the temperature of the releases calculated by this study.

With a maximum reservoir water surface of 3,700 ft, gates on four of the multiple-level intake structures were set at 3,470, 3,540, 3,580, 3,620 and 3,660 ft. Gates on the other four structures were set at elevations of 3,470, 3,520, 3,560, 3,600 and 3,640 ft. If a total of only four structures were installed, it would be assumed that two would have the first gate arrangement and the other two would have the second gate arrangement.

The model was run using an outflow of 28,000 cubic feet per second (cfs), which is near the full power release of the dam when all eight turbines are operating. Under the present operation scheme, all eight turbines are normally used for peaking power purposes on a daily basis during the months of June, July, August, and September. The model was run to give the maximum possible release temperature using the highest available intake gate levels. The full power release, 28,000 cfs, was also assumed for the four multiple-level intake structure option. The simulations were based on conditions existing at specific times in the past: the months of May through October in 1977, 1978, 1980, and 1982.

RIVER TEMPERATURE MODELING. The Graphical model equations provide a straightforward technique for estimating downstream water temperatures on the basis of meteorological conditions, including solar radiation, cloud cover, air temperature, wind speed, relative humidity, and atmospheric pressure. This model is capable of providing reasonable results given the minimal data collected in this study area.

The Qual-II method is a comprehensive and versatile stream quality model able to simulate up to 13 water quality constituents. The temperature constituent was the only one used for this study. This model allows the study area stream system to be subdivided into different reaches and to allow for tributary flows. The meteorological data used are similar to the data used by the Graphical model.

Both the Graphical and Qual-II models were calibrated using the monthly average temperatures collected by the USGS during 1983 at the five sediment sample stations: Lees Ferry (River Mile [RM] 0), Little Colorado River (RM 61), Phantom Ranch (RM 87.5), National Canyon (RM 166) and Diamond Creek (RM 225). The 1983 data were used because they were collected simultaneously throughout the study area. Modeling simulated conditions of the 225 river miles from Lees Ferry to Diamond Creek. Modeling did not start at Glen Canyon Dam because river temperature data from the dam to Lees Ferry were unavailable.

The river temperature models were also calibrated with Grand Canyon atmospheric data and the best available long-term atmospheric data collected at several other sites, including weather stations at Las Vegas and Phoenix, located several hundreds of miles from the Grand Canyon. Model input requirements and extent of available input data determined the level of calibration and verification. The paucity of both meteorologically and water quality data required that adjustments be made to the input data.

The Graphical model was calibrated assuming the same August 1983 atmospheric conditions for the total 225 river miles from Lees Ferry to Diamond Creek. The different reaches were not modeled separately because, with a few minor adjustments to the input conditions, the model simulated the August 1983 river temperature data collected at the five sampling stations.

The Qual-II model was divided into four river reaches corresponding to the five USGS sediment sampling stations: Reach 1 (Lees Ferry to the Little Colorado), Reach 2 (Little Colorado to Phantom Ranch), Reach 3 (Phantom Ranch to National Canyon), and Reach 4 (National Canyon to Diamond Creek). The average velocities for each reach were estimated using the SSARR (Streamflow Synthesis and Reservoir Routing) model (U.S. Army Engineering Division 1975) calibrated for the Colorado River by the Durango Projects Office.

Both calibrated models were run using initial starting river temperatures at Lees Ferry of 62 degrees F. A starting temperature of 70 degrees F, the calculated upper limit of the dam's outlet water temperature from the BSelect model, was also tested. The temperature of 62 degrees F was used because the trout fishery below the dam would still prosper, and it was hoped that the river temperatures would approach the pre-dam conditions 60 river miles downstream at the Little Colorado River confluence. The Little Colorado River is one of the existing native fish spawning areas below the dam, and the warming of the Colorado River water below Glen Canyon Dam could extend and increase those activities throughout the canyon.

RESULTS AND DISCUSSION

OUTLET TEMPERATURE MODELING (BSelect2). The BSelect model gave predicted release temperatures from the dam for the eight intake structure and four intake structure options based on the May-October 1977, 1978, 1980, and 1982 release patterns (Figure 2 and Table 2). These predicted temperatures were then compared to the pre-dam (1953) and post-dam (1977-1983) measured temperatures from the Lees Ferry station. The eight intake structures can increase the river release temperatures 5-18 degrees F over present conditions. This is still 7-16 degrees F cooler than pre-dam conditions. The four intake structure option would increase release temperatures only slightly (2-9 degrees F) over present conditions.

RIVER TEMPERATURE MODELING. The Graphical and Qual-II river temperature modeling results and the 1953 and 1983 measured river temperature data for August (Figure 3 and Table 3) show that river temperature increase is minimal as water flows from Lees Ferry to Diamond Creek. Assuming an initial river temperature of 62 degrees F at Lees Ferry, the models calculated the temperature increase to the Little Colorado to be only 1-2 degrees F, and the maximum increase to Diamond Creek to be only about 6 degrees F. Similar results

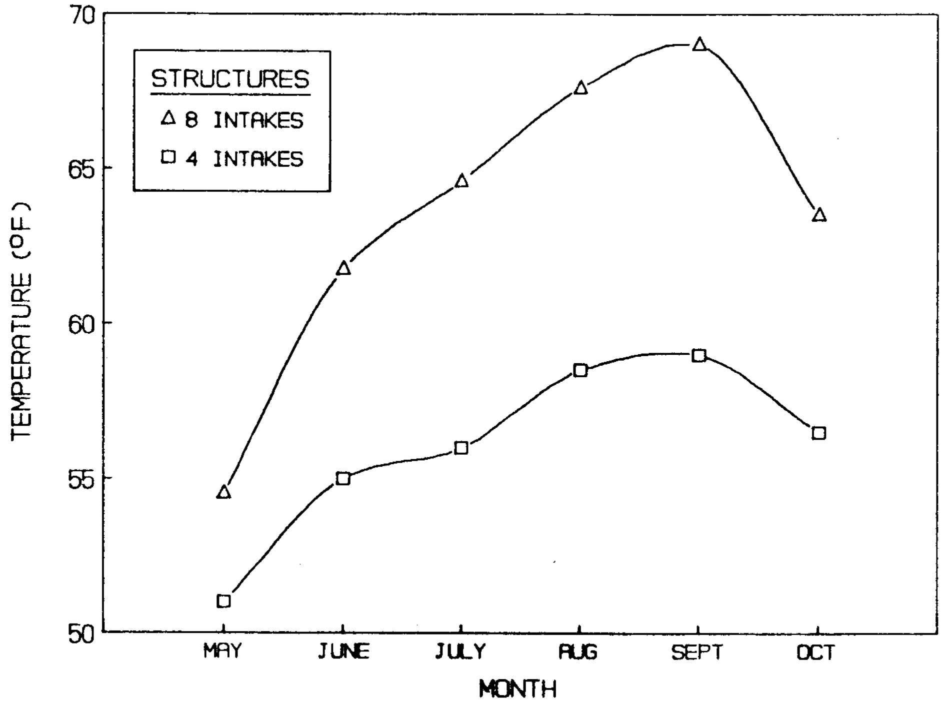

Figure 2. Predicted release temperatures from Glen Canyon Dam for eight and four multiple-level intake structures.

Table 2. Modeled and measured average monthly Colorado River temperatures (degrees F).

	BSelect2 Modeling Results: River Temperature Just Below Glen Canyon Dam				USGS Gaging Station At Lees Ferry	
	Year					
Month	1977	1978	1980	1982	Average	1977-1983	1953
May	-	-	55.0*	54.0*	54.4*	49.0	61.5
			(51.0)	(51.0)	(51.0)		
Jun	65.0*	64.0*	58.0*	60.0*	61.5	49.5	68.0
	-	(58.0)	(52.0)	-	(55.0)		
Jul	63.0*	-	65.0*	66.0*	64.5	50.0	80.5
	(56.0)	-	(56.0)	-	(56.0)		
Aug	64.0*	-	70.0*	69.0*	67.5	49.5	79.0
	(56.0)	-	(61.0)	-	(58.5)		
Sep	70.0*	-	68.0*	69.0*	69.0*	50.5	75.0
	(59.0)	-	(59.0)	-	(59.0)		
Oct	-	-	64.0*	63.0*	63.5*	50.0	-
	-	-	(57.0)	(56.0)	(56.5)		

* eight multiple-level intake structure option

( ) four multiple-level intake structure option

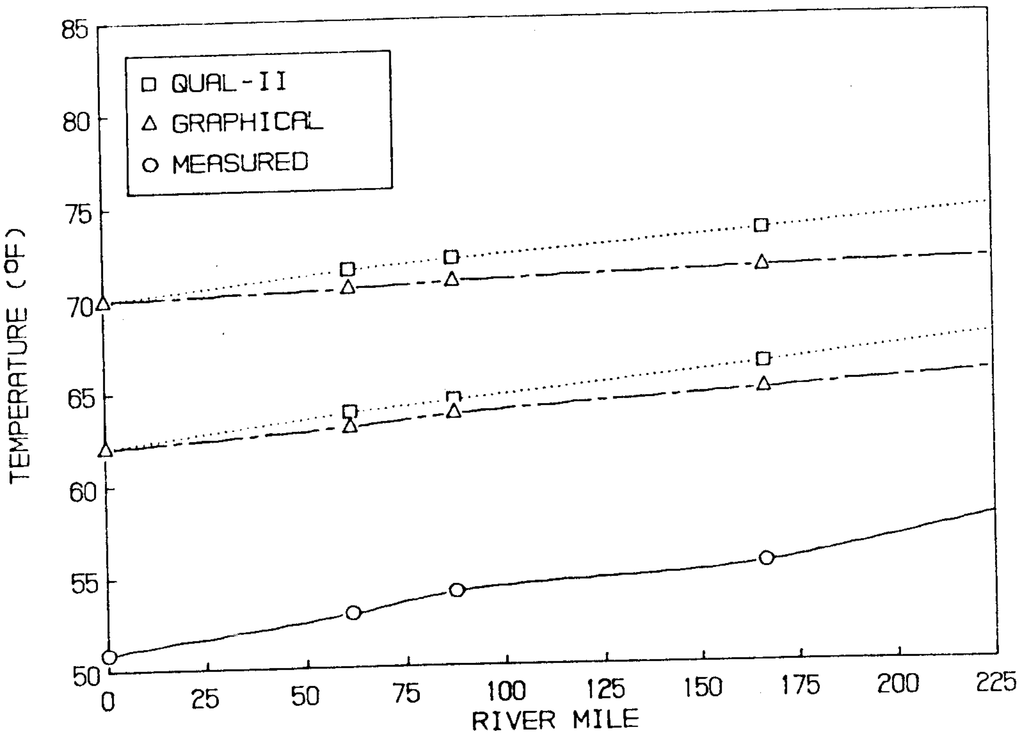

Figure 3. Average modeled (Graphical and Qual-II models) and measured August Colorado River temperature (degrees F).

Table 3. Measured and modeled average August Colorado River temperatures (degrees F).

	Measured		Modeled			
Location	1983	1953	Graphical		Qual II	
Lees Ferry	50.9	78.8	62.0	70.0	62.0	70.0
Little Colorado	52.9	-	63.0	70.5	63.8	71.5
Phantom Ranch	54.0	77.0	63.6	70.8	64.4	72.0
National Canyon	55.4	-	64.8	71.4	66.2	73.4
Diamond Creek	57.9	-	65.7	71.8	67.7	74.6

were found when the model was run for the months of June, July, and September using the same initial river temperatures. The 1983 measured river temperatures showed that, with an initial temperature of 50.9 degrees F at Lees Ferry, the increase to the Little Colorado was 2 degrees F, and the increase to Diamond Creek was about 7 degrees F. The small increase in water temperature as the river flows downstream is probably due to the high velocity of the river and the deep channel. These factors reduce both the time and the area of exposure to atmospheric conditions within the canyon that could warm the waters June through September.

The downstream river temperature modeling results are similar for the months of June through September because of the similarity of atmospheric and river conditions during these months. The release temperature from the dam is the determining factor for the downstream maximum river temperature in this period. The release temperature (Table 2) could vary (according to the BSelect2 model) from about 62 degrees F for June to 70 degrees F for August and September.

CONCLUSIONS

Multiple-level intake structures on all eight of Glen Canyon Dam's penstock intakes would increase river temperatures, but not to pre-dam levels. The Graphical and Qual-II river temperature models calculate only a modest increase in water temperature from Lees Ferry to Diamond Creek.

RECOMMENDATIONS

The Glen Canyon Environmental Study Team should analyze the preliminary results from this study and weigh the positive and negative effects of increasing the Colorado River water temperature. If it appears that increasing the river water temperature would benefit the Grand Canyon river environment, then the team should recommend that additional, in-depth studies be completed to assess the impact of such an increase on Lake Powell and the trout fishery below the dam, as well as the possible benefit to the Lake Mead fishery of increased nutrient inflows from Lake Powell.

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INSTREAM FLOW ANALYSIS OF THE GLEN CANYON DAM TAILWATER

Physical habitat modeling of the Colorado River within the Glen Canyon Dam tailwater was conducted using the Physical Habitat Simulation modeling program to determine the relationship between operation of Glen Canyon Dam and the habitat for rainbow trout over a range of discharges from 2,000 to 26,000 cubic feet per second. Refined habitat suitability data collected in 1986 were utilized to enhance a 1980 analysis. An evaluation of the 1980 and 1986 study results showed minimal changes in the amount of usable habitat area for trout following high flows in 1983.

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INTRODUCTION

On March 13, 1963, the gates at Glen Canyon Dam were closed, initiating major changes in the Colorado River's aquatic ecosystem. With the closure of Glen Canyon Dam and the filling of Lake Powell, controlled releases, reservoir-modified water quality, and temperature altered the character of the Colorado River. The river changed from a seasonally warm, sediment-laden stream to one with clear and constant cold water flows. The impact of dams on the downstream aquatic resources has been well documented (Ward 1974; Cummins 1979; Holden and Stalnaker 1975; Hickman 1983; and Vanicek, Kramer, and Franklin 1970).

In 1964, the Arizona Game and Fish Department (AGF) began stocking rainbow trout (*Salmo gairdneri*) (Brancroft and Sylvester 1978) in the dam's tailwaters. The trout were not native to this stretch of the Colorado River; therefore, special care and management were required to establish a viable fishery resource. The present tailwaters have developed into a world-class trout fishery. However, this aquatic ecosystem is an artificial environment resulting from the regulated flows from Glen Canyon Dam.

During the peaking power investigations at Glen Canyon Dam in 1980 (Bureau of Reclamation 1982), an instream flow study identified relationships between the operations of the dam and the trout fishery. After the 1983 high releases from the dam, the U.S. Fish and Wildlife Service (FWS) requested a revaluation of these relationships to determine if results of the 1980 studies were still applicable. The investigation reported here was conducted by the Bureau of Reclamation (BOR) in response to this request.

Objectives. This paper reports a reanalysis of the 1980 instream flow study using the Physical Habitat Simulation (PHABSIM) (Milhous, Wegner, and Waddle 1981) computer programs. The objectives of the reanalysis were to determine if the 1980 analysis was still usable after the impact of the 1983 high flow releases and to determine if refinement of the 1980 results could be made with the addition of more definitive trout habitat relationships.

METHODS

The information used in this study included: the 1980 instream flow hydrologic analysis developed under the Peaking Power Studies (Bureau of Reclamation 1982); the habitat suitability indices developed for the 1980 instream flow study (Bureau of Reclamation 1982); trout microhabitat studies conducted below Glen Canyon Dam (Gosse and Gosse 1985); and an analysis made of the aggradation/degradation that occurred in the Glen Canyon Dam tailwater as a result of the 1983 high flow releases (Bureau of Reclamation 1986). No new data was collected as part of this study.

The methods used were as follows: (1) an analysis of the stream bed of the Glen Canyon Dam tailwater made after 1983 was compared to data collected in 1980 to ascertain changes in aggradation and degradation; (2) an analysis was made of the 1980 instream flow study site hydrological analysis to allow for a complete listing of all the hydrologic and physical variables; (3) the 1980 instream flow hydrologic data were reanalyzed, (4) trout microhabitat data collected by Gosse and Gosse (1985) were used to develop Glen Canyon Dam tailwater-specific habitat suitability indices. These results were then compared to the 1980 habitat suitability indices; (5) using PHABSIM, the 1980 instream flow hydrologic data were re-run with the new habitat suitability data, and the results were compared to the original 1980 study results; and (6) an evaluation was made of the use of the original and the revised Glen Canyon Dam tailwater studies.

Study Site. In 1980, a representative reach of the Glen Canyon Dam tailwater was chosen for the instream flow study. The site was located approximately six miles below Glen Canyon Dam, within the Glen Canyon National Recreation Area. Eleven transects were selected to represent instream hydraulics and the aquatic habitat.

The study site was selected to represent the primary types of aquatic habitats of the Colorado River within the Glen Canyon Dam tailwater. It does not represent the entire range of aquatic habitats through the Grand Canyon. The study site is characterized by a slope of three feet per mile and contains no rapids. Several riffles do appear at lower water levels as cobble bars are exposed. Due to its close proximity to Glen Canyon Dam, the influences of hydroelectric generation releases are quickly manifest.

The water quality of the study site reflects the hypolimnion (deep water) releases from Lake Powell. Variation of the water quality parameters result from the seasonal flows and limnological characteristics of Lake Powell. The seasonal short-term variation is relatively minor; however, long-term variation in conductivity, productivity, and temperature were observed (Miller, Wegner, and Bruemmer 1983).

The three physical habitat variables used to define the aquatic habitat in the Glen Canyon Dam tailwater instream flow study were mean column velocity, depth, and substrate. Measurements of these variables were made at intervals along the transects in the study site at discharge levels of 2,000, 16,000 and 26,000 cubic feet per second (cfs) during the months of February, April, and June 1980.

Color aerial photographs were taken of the study site at a flow of 5,000 cfs. The 11 study transects were identified on the photos at a scale of 1:4800, where 1 inch equals 400 feet. Cross-sectional plots of the 11 transects were developed and used to identify habitat locations at the measured and modeled flow levels.

The 1985 Reanalysis. To determine if the hydraulic conditions below Glen Canyon Dam, as measured in 1980, had changed as a result of the 1983 flood releases from Glen Canyon Dam, and if the 1980 hydrology data were used accurately to represent the Glen Canyon Dam tailwater study site, a cross-sectional analysis of the river channel between Glen Canyon Dam and Lees Ferry (a distance of 16 miles) was made.

The analysis was based on surveys of 12 previously defined evaluation sites established from the dam down to Lees Ferry by BOR after the closure of Glen Canyon Dam in 1963. The purpose of establishing these transects (range lines) was to provide consistent and long-term locations where channel-change characteristics could be monitored. Two of the 12 range lines are located within this study's research site: Range Lines 19 and 11A. In October 1983, BOR surveyed the 12 sites (Bureau of Reclamation 1986). A comparison was made of the 1983 surveyed profile and cross sections to the pre-1983 high flow range line measurements to quantify what change may have occurred.

Model Calculation. The physical aquatic habitat variables of the study site were modeled using the Physical Habitat Simulation (PHABSIM) computer model developed by the Instream Flow and Aquatic Systems Group (IFG-4) of the FWS (Milhous, Wegner, and Waddle 1981; Bouvee 1982). The PHABSIM system consists of computer programs used to related changes in water discharge to changes in physical habitat availability. The underlying principles of PHABSIM are: (1) each species exhibits preferences within a range of habitat conditions that it can tolerate, (2) the ranges can be defined for each species, and (3) the area of stream providing these conditions can be quantified as a function of discharge and channel structure (Bovee 1982).

A natural stream is a complex mosaic of physical features. As flow levels (discharges) change, the combinations of available habitat are altered. For example, in a given stretch of the river, lowering the discharge will reduce the water depth. This in turn affects light penetration, water temperature, pressure, availability of space, etc., all factors pertinent to use of that location by fish. Any given location will become more or less usable as a result of the change in discharge.

PHABSIM describes the mosaic of aquatic habitat on the basis of defined transect lines which are used to show the distribution of the different hydrological and habitat conditions within the study site. Field measurements of water depth, velocity, and bottom substrate type are made at points long the transect line. The resulting information is a quantification of the study site as a series of transects and "cells" of physical habitat area. Cells are measured intervals on the transects that delineate areas of habitat extending in two-dimension: along the transect and from the water surface down to the riverbed.

The usability of each cell for an aquatic species is then evaluated by applying the known habitat criteria for that species. In this way, the hydrologic relationships are "weighted" by the habitat's suitability for use by the fish in question. The end result of the PHABSIM's analysis is an evaluation of the habitat potential of the individual cells and a composite estimate of habitat potential within the study site. This index, labeled the "Weighted Usable Area," varies by flow level, aquatic species, and life stage.

Modeling for the study consisted of four phases: (1) preparation of the data input files for PHABSIM; (2) hydraulic simulation modeling, using the program IFG-4, of the depth, velocity, and substrate characteristics as a function of discharge; (3) development of the biological suitability relationships (probability for trout use as related to dam discharge); and (4) calculation of the habitat responses over the range of discharges.

<u>Hydraulic Simulation.</u> The hydraulic simulation for the study site was based on the field data collected in 1980. The IFG-4 hydraulic simulation model (Milhous, Wegner, and Waddle 1981) was used to develop a series of linear regression equations for (1) river level (depth) versus dam discharge for each transect in the study site and (2) river velocity versus dam discharge for each cell measured along the transect. To verify the validity of using the simulated data to interpolate flows, the calculated dam discharges, river levels (depth), and internal velocities were compared to the measured values from the study site.

Upon completion of the hydraulic simulation of the study reach, the estimated depth and velocity relationships, measured discharges, substrate data, and distance between transects were combined with a numerical measure of the habitat requirements (called habitat suitability indices) for adult, juvenile, and fry life stages of rainbow trout. This was done to evaluate the biological usefulness of the study site to trout.

<u>Habitat Suitability Indices.</u> Habitat suitability indices are a dimensionless index bounded by 0.0 and 1.0, where 0.0 represents no usable habitat and 1.0 represents optimal habitat. Habitat suitability curves have been developed for trout (Bouvee 1978), but their application to large western rivers has been limited.

The premise for development of the habitat suitability indices for the study site assumed that individual trout will select the most preferred habitat in the river when given a choice, and that the individual life stages will require different habitats. Poor habitat is less likely to be used by trout. It was assumed that this range of use could numerically be defined on a scale of 1.0 to 0.0. It was further assumed that individuals would leave an area when it becomes totally unsuitable for their needs.

The habitat suitability indices used in the 1980 instream flow analysis were composites of empirical, hypothesized, and existing information from small streams and rivers. Consequently, the results were biased. To avoid a similar bias, the indices developed for the 1985 habitat reanalysis were based on actual measurements made in the Glen Canyon Dam tailwater.

These measurements resulted from studies conducted by Gosse and Gosse (1985) in the Colorado River below Glen Canyon Dam during the summer of 1984 and the winters of 1984 and 1985. The Gosses surveyed trout habitat to determine if there were seasonal (winter versus summer) differences in trout habitat requirements. The habitat surveys analyzed the aquatic environment variables that would or could change with small changes in the trout's location. Seven aquatic habitat variables were measured for each trout observation: fish velocity, mean column velocity, fish depth, water depth, distance to cover, overhead light, and substrate type. In addition, an analysis was made to determine if the trout exhibited different activity responses during the seasons. Gosse (1982) categorized the life stages of trout as follows: fry were 12 centimeters (cm) or smaller, juveniles were 12 to 27 cm, and adults were fish longer than 27 cm.

Using these data, new habitat suitability indices were developed for water depth and mean column velocities for adult, juvenile, and fry life stages of rainbow trout in the study site. The suitability indices were further expanded by evaluating seasonal, activity, and life stage differences. The indices were calculated using frequency analysis, curve fitting, and tolerance intervals as outlined by Bovee and Cochnauer (1977) and Bovee (1982). The 1980 and 1985 habitat suitability indices were then compared to determine if significant differences occurred between years, seasons, and activity levels.

Weighted Usable Area. To complete the simulation, the 1985 habitat suitability indices were combined with the hydraulic characteristics of the IFG-4 analysis to calculate an index of potential use: the Weighted Usable Area. An expanded flow regime of 1,000 to 60,000 cfs was modeled to predict the overall habitat response over a wide range of Glen Canyon Dam releases. Analysis was by season, life stage, and flow regimes. "Available habitat" was computed and the results were organized into tables defining the habitat availability by life stage versus discharge level. Summer and winter seasonal trends were combined to develop annual relationships. The 1980 and 1985 results were then compared.

Model Assumptions. The following assumptions were used in the application of the PHABSIM (Orth and Maughan 1982; Bovee 1982): (1) depth, velocity, and substrate are the most important habitat variables affecting fish distribution and abundance when changes in flow regime are considered; (2) the river channel is stable and not altered by changes in the discharge levels; (3) depth, velocity, and substrate independently influence habitat selection by the target species; (4) the habitat/discharge relationship can be modeled on the basis of a representative reach for the stream segment in question; and (5) a positive and linear relationship exists between the weighted usable area and habitat use.

RESULTS AND DISCUSSION

To complete the objectives of this study, it was necessary to (1) determine how valid the results of the modeling were and (2) determine how the results could and should be used. A review of the 1980 analysis indicated that several inherent errors were made in the development of the original hydrologic and biological data bases and in the use of the results in making impact assessments. The information presented in this section will identify the major problem areas in the 1980 analysis as compared to the work completed under this study. The intent is to identify how the information generated under the 1980 and this study should be used.

Profile Analysis. Based on the evaluation of the surveyed BOR range lines, it was concluded that a large scale change in the integrity of the river channel had not occurred, and that the channel geometry data collected in 1980 are still representative of the 1985 river channel. A cumulative gain in area of 1,272 square feet occurred at the Range Line 10 site and a net loss of 780 square feet occurred at Range Line 11A. This represents only a three percent change in the actual volume of material at these two sites.

Hydraulic Simulation. The IFG-4 calculated values of discharge, water surface elevations, and velocity were compared to the 1980 measured hydraulic values with the following results. The calculated water surface elevations compared to within ten percent of the measured values. The calculated mean column velocities of the main channel compared to within ten percent of the measured values; however, the calculated mean column velocities for the nearshore areas showed a great deal of variability, with a range from 10 to 30 percent.

A measure of the match of the IFG-4 calculated versus actual interval velocity values (Table 1) is the "Velocity Adjustment Factor" (VAF). A VAF value within the range of 0.90 to 1.10 indicates a good fit to the data set and consequently provides a verification for the calculation of interpolated flows (Milhous, Wegner, and Waddle 1981). A VAF value of 1.0 represents a perfect fit to the data set for the study site.

All transects except numbers 8 and 9 at 2,000 cfs and 26,000 cfs indicate an acceptable fit of calculated velocity values. Low velocity adjustment factors for transects 8 and 9 indicated the hydraulic relationships were unstable. Therefore the results of the analysis should be used with caution.

Habitat Suitability Indices. The 1985 refinement of the 1980 habitat suitability indices resulted in improved modeling and prediction of the habitat relationships of the rainbow trout below Glen Canyon Dam. Refinement of the results was in the quantification of the available and preferred habitat.

The 1980 habitat suitability indices of depth relationships for the adult, juvenile, and fry life stages of the rainbow trout indicated differences when compared to the 1985 habitat suitability indices based on actual field measurements. A comparison of the optimum levels of depth and range of depth most preferred for the three rainbow trout life stages is shown by Table 2.

Table 1. The Velocity Adjustment Factors for the Glen Canyon Dam tailwater study site in relation to the three measured discharges. ("*" indicates an unacceptable fit.)

Transect	2,000 cfs	16,000 cfs	26,000 cfs
1	0.95	0.99	0.95
2	1.01	0.99	0.96
3	1.01	1.0	0.96
4	0.99	1.0	0.98
5	0.95	1.03	0.94
6	0.98	1.0	0.94
7	0.91	0.96	0.97
8	0.74*	0.99	0.80*
9	0.79*	0.99	0.77*
10	0.96	1.02	0.98
11	0.95	0.99	0.94

Table 2. Comparison of 1980 and 1985 Habitat Suitability Indices (HSI) by Optimum Depth Preferences for three life stages of rainbow trout.

Life Stage	1980 Depth HSI (feet)	1985 Depth HSI (feet)
Fry	0.6 to 1.0	2.5 to 6.0
Juvenile	0.7 to 1.1	12.3 to 16.0
Adult	1.6 to 50.0	15.0 to 20.0

The 1985 habitat suitability indices reflect a preference for deeper water than was reflected in the 1980 analysis. The utilization and location of the most preferred aquatic habitat are restricted to specific depths with fry utilizing the nearshore, shallow habitat areas, and the adults and juveniles utilizing deeper water habitats along the channel margins. The 1985 depth data reflect a more close approximation or refinement of the trout habitat use and are consistent with existing knowledge of Glen Canyon Dam tailwater trout physiology, dynamics, and behavior (Brancroft and Sylvester 1978.)

The 1985 indices also reflect a refinement of trout activity levels. Two distinct types of activity levels have been identified for trout in rivers: **random swimming activity** exhibiting little or no orientation to current velocity; and **stationary swimming activity**, with a decided orientation to the current of the river. Random swimming activities have been hypothesized to reflect an energy conservation measure, while a stationary swimming activity level reflects an active response to feeding and habitat utilization (Gosse and Gosse 1985). Fish showing random swimming actions are not focussed on specific habitat niche while stationary swimming fish are. Analysis of the Gosse and Gosse (1985) data for the Glen Canyon Dam tailwater indicates that the trout exhibit variability in activity levels between the juvenile and adult life stages. The majority of observations of adult and juvenile rainbow trout exhibited a stationary swimming activity with an orientation to the current.

In studies conducted on trout in the Flaming Gorge tailwater of the Green River in Utah (Wegner and Williams 1985; and Gosse 1982), a change in the physical activity level was correlated with a seasonal shift in habitat requirements. The adult and juvenile rainbow trout exhibited a predominant stationary swimming activity from May through September and a random swimming activity from November to March. The Glen Canyon Dam tailwater trout do not appear to exhibit the same seasonal shift in habitat requirements. We ran a chi-square statistical analysis test on the differences between the activity levels (Random versus Stationary) and seasons (Summer versus Winter), at a probability level of 0.05. From the analysis, it was determined that no seasonal difference in trout habitat preferences exist in the Glen Canyon Dam tailwater. However, the trout do exhibit periodic, short-term shifts in activity levels as a compensation for the physiological stress of habitat shifting as the releases from Glen Canyon Dam fluctuate.

An area of concern is how much of the river channel is used "actively" by trout for food gathering and shelter, and how much of the river channel is used secondarily for movement. Gosse and Gosse (1985) identified that the trout primarily used the nearshore areas around cobble bars, and the reduced velocity zone near the bottom of the river channel. Limited use was made of the main channel as the velocities are unsuitable and cover unavailable.

In small trout streams the fish can typically use a large percentage of the available physical habitat. In larger streams and rivers, trout use a relatively smaller percentage of the total aquatic habitat because velocity and depth relationships are unsuitable. This is true of the Glen Canyon Dam tailwater, where trout can actively utilize only a small percentage of the total amount of aquatic habitat available. The remainder of the aquatic habitat is used primarily for movement from one location to another.

Weighted Usable Area Relationships. The WUA values reflect the changing relationships of usable aquatic habitat and discharge levels. Weighted usable area for the Glen Canyon Dam tailwater study site was calculated for rainbow trout adult, juvenile, and fry life stages. The maximum WUA occurred at 18,000 cfs for adult, 12,000 to 18,000 cfs for juvenile, and 9,000 cfs for fry life stages respectively.

The analysis of the changes in cross-sectional habitat location at the 11 transects reflects a shifting of the amount and location of usable trout habitat as the discharge level fluctuates from low to high and back to low.

It has been noted (Bureau of Reclamation 1982) that numerous trout do become stranded in isolated pools and on spawning bars as dam releases fluctuate. The maximum flows, minimum flows, and rate of change of the releases are important components of stranding.

The Weighted Usable Area calculation for the study reach and short-term relationships reflect only the relationship between the trout and the parameters of depth, velocity, and substrate. In an ecological reality, a more complex and dynamic relationship exists among these parameters, as well as food resources, habitat quality, and the total life history requirements.

SUMMARY AND CONCLUSIONS

This study presents a synopsis of a hydrologic and biologic simulation of the flow-habitat relationships in the Glen Canyon Dam tailwaters. The actual amount of usable area in 1985 was calculated and compared to the 1980 results, and differences were minimal. Only general trends of habitat utilization were shown. The trout habitat requirements used in the 1980 analysis were modified to reflect conditions specific to the Glen Canyon tailwater area.

Results of this study should only be used to identify trends in habitat utilization by rainbow trout. These data should not be used to address more specific relationships such as areas of movement and actual amount of fry, juvenile, and adult habitat. Additional field data are necessary to expand application of the data to other areas of interest.

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THE EFFECTS OF STEADY VERSUS FLUCTUATING FLOWS ON AQUATIC MACROINVERTEBRATES IN THE COLORADO RIVER BELOW GLEN CANYON DAM, ARIZONA

The objective of this report is to determine impacts of steady versus fluctuating discharges on aquatic macroinvertebrates. Specific objectives include: identify impacts on invertebrate drift, specifically the amphipod Gammarus lacustris; determine standing crop and distribution of aquatic macroinvertebrates under various flow regimes; and quantify the relationship between biomass of Cladophora glomerata and standing crop of Gammarus lacustris. Further detailed information regarding this research can be found in Leibfried and Blinn (1987).

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INTRODUCTION

The operations of Glen Canyon Dam are primarily in response to power demands within the Colorado River Storage Project system. In past years this demand resulted in a peaking power operation that would cause river discharges to fluctuate daily. It was not uncommon to have ranges of 3,000 to 15,000 cubic feet per second (cfs). The effect of these fluctuations was the creation of an "intertidal" zone along the margins of the Colorado River. In 1980, Lake Powell reached full capacity, and since that time, the range of fluctuating discharges has been decreased. Proposed peaking power operations might possibly increase the range of fluctuations and increase the duration of low flows. This proposed operation would increase the size of the "intertidal" zone, possibly decreasing available habitat for algae and invertebrate species.

Ward (1976a) determined that dams with hypolimnetic releases alter natural seasonal and diurnal temperature regimes that regulate invertebrate life cycles and development patterns. Ward concluded that deep release dams produce low diversity and high standing crop of invertebrates that can adapt to thermal constancy. The aquatic ecosystem in the tailwaters of Glen Canyon Dam shows the same trend, i.e., few invertebrate species (Gammarus lacustris and chironomids) dominate with high standing crops (Carothers and Minckley 1981; Hofknecht 1981). The proliferation of the filamentous green alga

Cladophora glomerata and its associated epiphytic diatoms in the regulated Colorado River has increased the habitat and food base for invertebrate species. The importance of increased vegetation for aquatic invertebrate production is well established for European and North American rivers (Hynes 1970; Ward 1976b). Gosse (1981) established a relationship between algal beds and invertebrates specifically for the Colorado River below Glen Canyon Dam. The results of this study will add substantially to our knowledge regarding the influence of flow releases on aquatic macroinvertebrates in the Colorado River.

METHODS

Due to restraints of power production and lake level maintenance, discharges from Glen Canyon Dam were variable during the course of this study. Prior to initiating the field collections, it was agreed that the U.S. Bureau of Reclamation would provide steady releases from the dam from May through September 1985 and would fluctuate flows from October through December 1985. However, all flows observed during the study fluctuated to some degree. May through September "steady" flows fluctuated less than 8,000 cfs at one time and usually water level did not rise or fall drastically. October through December flows fluctuated far more, with discharges rising from 2-3,000 cfs to greater than 20,000 cfs in less than two hours.

Invertebrate drift was sampled at one site 10.5 miles above Lees Ferry. Collections were made over a 24-hour period in each of the months of steady flow (May, June, July, August, and September 1985) and in each month of fluctuating flow (October, November, and December 1985). During each 24-hour period, drifting invertebrates were sampled at four-hour intervals, insuring that steady, increasing, and decreasing discharges were represented. Flow releases for at least two weeks prior to any drift samples reflected the conditions of study for that period, i.e., fluctuating or steady discharges.

Benthic macroinvertebrates were sampled for distribution and standing crop estimates at selected sites that coincided with the Arizona Game and Fish Department's five study reaches from Glen Canyon Dam to Diamond Creek on the Colorado River. Sites were chosen to include the Colorado River mainstream, selected tributary mouths, and the zone of influence in the main river below the mouths. Lees Ferry, Nankoweap, Bright

Angel, Above Tapeats, and 220 Mile were mainstream sites. The Little Colorado River, Tapeats Creek, and Kanab Creek were sampled for organisms in the mouths and zone of influence below each. A modified Hess bottom sampler was used to sample benthic invertebrates during July, October, and December 1985.

A study site for quantifying the relationship between Cladophora and Gammarus was established at 13.5 miles above Lees Ferry. Using SCUBA (Self Contained Underwater Breathing Apparatus), collections were made during July and October 1985 and in January and March 1986. The study site was chosen to allow a diver safe access to Cladophora covered rocks that could be easily removed from the substrate in moderate current. A diver, using a net to minimize loss of vertebrates, would randomly select rocks of various sizes and algal biomass. Depth of collections varied from 2.5 to 4 m, depending on river stage at time of sampling. This collection area was never exposed during periods of fluctuating discharges, with the possible exception of several extreme low discharges of less than 2,000 cfs in December 1985.

All field samples were returned to the laboratory for enumeration and biomass measurements. Identifications were aided with the use of Merritt and Cummins (1970) and Pennak (1953).

RESULTS

A significant positive correlation exists between an increasing range of discharges and drift of Gammarus lacustris ($P<0.01$, $n=66$, $r=0.48$; Figure 1). There is no correlation between Gammarus drift and absolute volume of flow from Glen Canyon Dam ($r=0.05$, $n=333$). Only during October, November, and December did drifting Gammarus increase as discharge increased. It was also only during these months that flows fluctuated more than 10,000 cfs.

Fluctuating discharges from Glen Canyon Dam increased the mean monthly drift of the amphipod Gammarus lacustris, but did not affect the drift of chironomids (midges). The filamentous green alga Cladophora glomerata was only slightly more abundant in the drift during this time. Mean drift rates of Gammarus increased from 10.7 organisms/hour for the months of steady flows (May, June, July, August, and September) to 42.3 organisms/hour for the three months of (Table 1). This is nearly a 20-fold increase. Mean drift

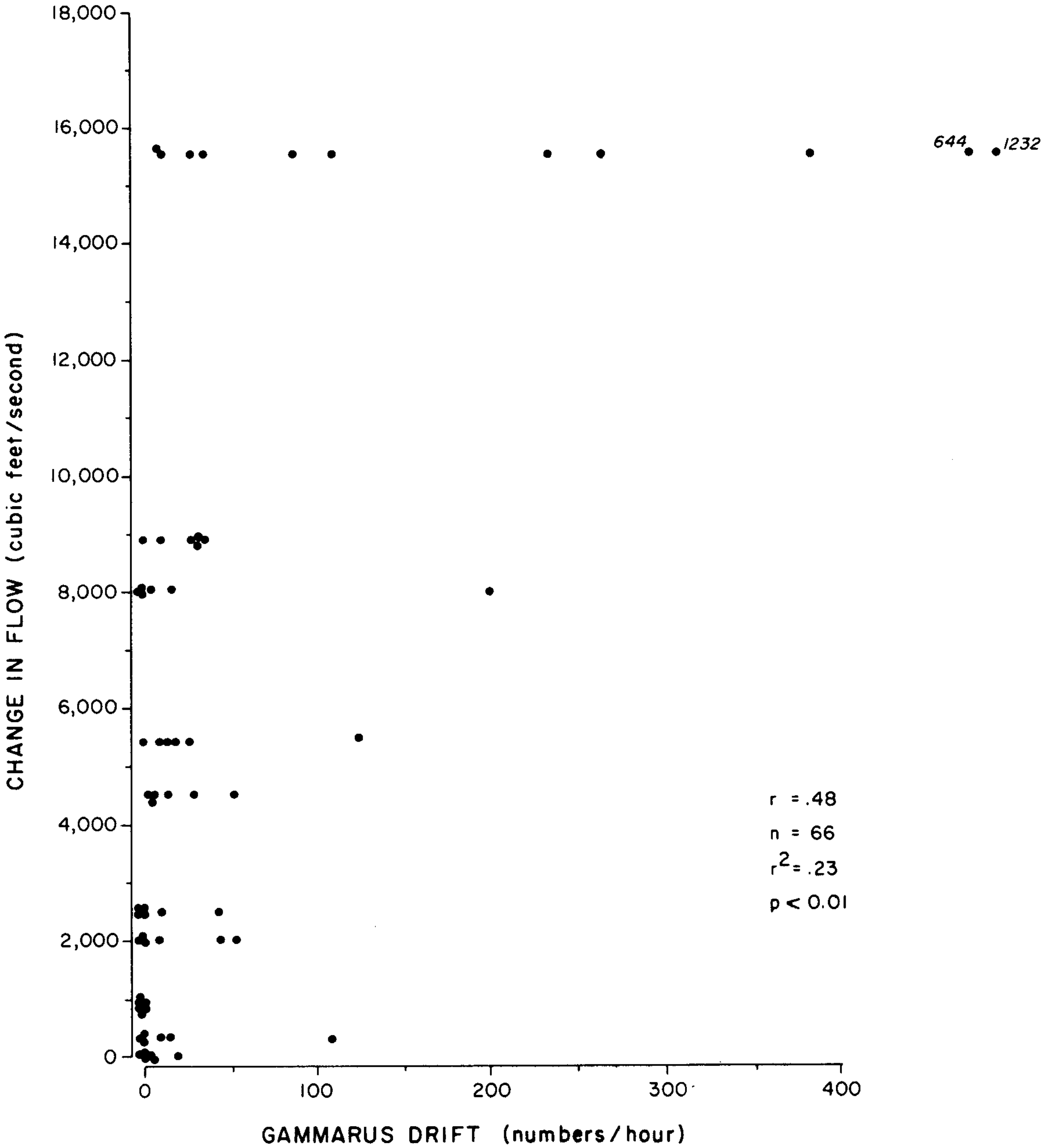

Figure 1. Correlation between change in flow and Gammarus drift rate for May-December 1985. Flows are given as increase in flow prior to drift collections.

densities fluctuating flows (October, November, and December) (number of organisms/100 cubic feet of water) for *Gammarus* and chironomids followed mean drift rates. *Cladophora* mean drift densities (g/100 cubic feet of water) remained constant (Table 1).

Table 1. Comparison of mean drift rates and densities in the Colorado River at Lees Ferry, Arizona, for months of steady versus fluctuating discharges during 1985. (Densities are per 100 cubic feet of water.)

	Steady (May - Sept.)	Fluctuating (Oct., Nov., Dec.)
# *Gammarus*	10.7/hr 0.14/100 cubic feet	42.3/hr 0.41/100 cubic feet
# Chironomids	402.5/hr 5.27/100 cubic feet	306.1/hr 3.74/100 cubic feet
Cladophora (grams dry wt.)	8.29/hr 0.10/100 cubic feet	6.85/hr 0.10/100 cubic feet
Total Biomass Per Day	0.70 *Gammarus* (15.4%) 3.86 Chironomid (84.6%)	2.85 *Gammarus* (49.2%) 2.94 Chironomid (50.8%)
(grams dry wt.)	4.56	5.79

Total drifting biomass of macroinvertebrates appears to have been influenced by fluctuating discharges. Drift biomass increased from 4.56 grams/hour under steady flows to 5.79 grams/hour under fluctuating flows. The percent contribution to the biomass drift rate from *Gammarus lacustris* increased from 15.4 percent under steady flows to 49.2 percent under fluctuating flows (Table 1).

An important factor controlling *Gammarus* drift below Glen Canyon Dam was the cycle of flow releases. During rising flows after periods of low flow (<5,000 cfs), amphipod drift rates and densities increased substantially. In November, drift rate of *Gammarus* increased to over 500 organisms/hour, the highest of any month surveyed. Although Bureau of Reclamation flow data reported discharges of 5-6,000 cfs prior to the increases in flow and consequent rise in drift, discharges were closer to 1,500 cfs (David L. Wegner, pers. comm.) A similar trend was observed in December samples when flows rose from 2,000 to 18,000 cfs. October data reinforce the hypothesis that flows control drifting organisms. During this sample period, flows of less than 5,000 cfs were not encountered and drift rates and densities remained low.

Benthic macroinvertebrate taxa encountered during this study included forms that predominated in the mainstream of the Colorado River and those forms that are characteristic of tributary streams. Mainstream taxa include: the amphipod Gammarus lacustris, Chironomidae (midges), Gastropoda (snails), and Oligochaeta (freshwater earthworms). Tributary taxa include: Trichoptera (caddis flies), Ephemeroptera (mayflies), Plecoptera (stoneflies), Simuliidae (black flies), Acarina (mites), Coleoptera (beetles), and Lepidoptera (moths).

The greatest invertebrate standing crops were observed where biomass of Cladophora glomerata and densities of epiphytic diatoms were also high. Mainstream Colorado River sites above the Little Colorado River averaged 1,153 total organisms/square meter while mainstream sites below the confluence had a mean of 329 organisms/square meter. Gammarus standing crop was 95 individuals/square meter in the mainstream above the Little Colorado River and 39 individuals/square meter below the confluence ($F_{1,180}=11.73$, $P<.001$). After comparing pooled data from below tributary mouth sites with pooled data from mouth sites, we concluded that more Gammarus were found at sites below the mouth of tributaries (26 individuals/square meter) than in the mouths themselves (11 individuals/square meter). On the average, mainstream sites had a higher standing crop than at tributary mouths or at below-mouth sites.

Total organism standing crop declined significantly ($F_{2,140}=5.9$, $P<.003$) from July to December 1985 (Figure 2). July collections were made under steady flow conditions, October collections were made after two weeks of fluctuating flows, and December collections represent conditions after three months of fluctuating discharges.

Two-way ANOVA, using date and kind of site (mainstream, mouth, or below-mouth) for total organism standing crop, showed that mainstream sites declined significantly ($F_{2,173}=3.01$, $P<0.05$) with the onset of fluctuating discharges in October and continued to decline in

December. Sites below tributary mouths also decreased significantly from July to October. These reductions were mainly due to the loss of chironomid standing crop during fluctuating flows. These midges were commonly the most abundant organisms collected. Cladophora biomass decreased as the frequency of fluctuating flows increased (Usher et al. 1987).

The relationship between the amphipod Gammarus lacustris, and the filamentous green alga Cladophora glomerata was determined using correlation analysis for four different seasons. Positive correlations were determined for July 1985 ($r=0.51$, $P<0.05$, $n=13$) and October 1985 ($r=0.92$, $P<0.01$, $n=20$) between Gammarus density (numbers/square meter) and Cladophora biomass (grams/square meter). Collections sampled in January and March 1986 had no correlation between Gammarus and Cladophora. Only during the October 1985 sample did Gammarus biomass (grams/square meter) show a positive correlation ($r=0.73$, $P<0.01$, $n=20$) with Cladophora biomass. Pooled data for all four months had a high positive correlation ($r=0.84$, $P<0.01$, $n=73$) for Gammarus density and Cladophora biomass.

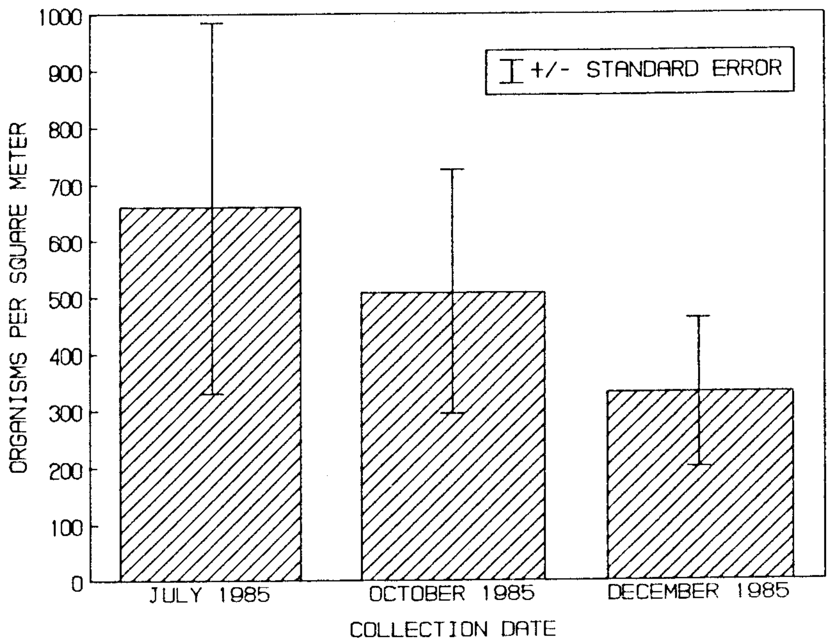

Figure 2. Total invertebrate densities for all taxa collected from the Colorado River at all sites below Glen Canyon Dam, Arizona. July collections were made during steady flows, October collections after two weeks of fluctuating flows, and December collections after three months of fluctuating flows.

Density and biomass of Gammarus lacustris and Cladophora biomass changed substantially from July to October 1985. Gammarus density and biomass increased with the onset of fluctuating flows in October 1985, while Cladophora biomass decreased. Reductions in Gammarus density and biomass as well as Cladophora biomass occurred in January 1986. A further decline in biomass and density of amphipods continued in March 1986, with Cladophora biomass increasing during this period.

DISCUSSION

In the Colorado River below Glen Canyon Dam, the effect of regulated discharges on invertebrate drift has never been fully documented. It is possible that if invertebrate drift increases under fluctuating discharges, this easily accessible food resource may allow for greater growth of fish species. An objective of this study was to quantify the drift of aquatic invertebrates under steady and fluctuating flow regimes. The results indicate that only during extreme periods of fluctuating discharges, 2,000 to 18,000 cfs, does drift of the amphipod Gammarus lacustris increase over levels found under more steady discharges. During the month of October 1985, fluctuations from Glen Canyon Dam ranged from 9,000 to 21,000 cfs, but drift did not increase from levels found under steady conditions.

The importance of algae as a food source and refugium for aquatic invertebrates is well known and reviewed by Hynes (1970) and Minshall (1984). Once Gammarus are established in the thick Cladophora beds below Glen Canyon Dam, large standing crops may result. When these beds are exposed, the amphipods, being highly mobile, try to crawl towards the water (pers. obs.). At this time they are extremely vulnerable, and should the flow of the river increase quickly, large numbers of Gammarus would be forced into the drift. The decreases and increases in the rate of flow will affect the numbers of drifting amphipods. If the decrease is slow, the organisms will be able to reach the water before the rising current will take them into the drift. A fast decrease followed by a fast increase in flow may result in higher drift rates than a gradual fluctuation.

Mean chironomid drift rates and densities were not affected by fluctuating discharges. For the months of fluctuating flows and some steady flow months, there is a relationship between chironomid and Cladophora drift. As more Cladophora is observed during the rising flows, more chironomids are also present. This could be the result of the lack of mobility of larval chironomids that are trapped within the Cladophora filaments as they are torn from the substrate and put into the drift.

Due to the short duration of fluctuating discharges for this study, drift data for November and December should only be taken as short-term effects. Longer periods of fluctuating flows should be studied to determine if a net loss of invertebrate standing crop will occur with continuous fluctuations. Drift studies by Iversen and Jessen (1977) indicate a significant net loss of invertebrates downstream. Walburg et al. (1983) reported that benthic production more than compensated for catastrophic drift resulting from discharge fluctuations in a southeastern U.S. river. It is possible that benthic production in the Colorado River below Glen Canyon Dam may not compensate for downstream drift losses.

The distribution and standing crop of benthic macroinvertebrates in the Colorado River have been altered extensively by regulated flows from Glen Canyon Dam (Carothers and Minckley 1981; Cole and Kubly 1977). The hypolimnetic releases from Glen Canyon Dam produce clear and consistently cold (10-11 degrees C) water releases. Pre-dam seasonal floods that scoured the river bottom are now regulated and replaced by daily fluctuations in response to energy needs. These fluctuations create an "intertidal" zone along the margins of the Colorado River below the dam.

The lack of pre-dam scouring floods and new clear, cold discharges has allowed for dense growths of the filamentous green alga Cladophora glomerata. It is in those areas of most productive algal growth that the highest standing crop of benthic invertebrates occur. The significant decrease in density of organisms below the confluence with the LCR parallels the significant decrease of Cladophora glomerata found by Usher et al. (1987). During December at the Above Tapeats and Below Tapeats sites, as well as in July at Below Kanab, Gammarus densities were high. This corresponds to increases in Cladophora biomass during these times (Usher et al. 1987). This trend is similar for total organisms collected at these sites. At sites that had limited algal production, LCR Mouth, Below LCR, Kanab Mouth, 220 Mile, and Below Kanab during October and December, invertebrate standing crop was usually lower than sites with higher Cladophora biomass.

The decline in total organisms collected may be directly related to increased fluctuating flow patterns (Figure 2). Although only three collections were made for this study, and data are insufficient to draw conclusions, the influence of seasonality could be concealed by the stronger effects of fluctuating flows. With the lack of seasonal water temperature changes, however, it is unlikely that invertebrate life cycle patterns would be as important in the mainstream Colorado River as in systems with more variable temperatures (Ward 1976b; Ward and Stanford 1979). After three months of fluctuating flows, Gammarus density decreased above the confluence of the Little Colorado River, but increased at those sites below the confluence. It is possible that the fluctuating discharges during December allowed Cladophora to receive more light, but did not lower algal biomass, thereby enhancing the habitat for these invertebrates.

A significant correlation exists between density of Gammarus lacustris and biomass of Cladophora glomerata. These data support previous work that established the importance of vegetation for amphipod species (Marchant 1981; Pennak and Rosine 1976). Data sets from the months of July and October 1985 each show significant correlations between amphipod standing crop and Cladophora biomass. January and March 1986 data did not show this relationship. Since samples were made at depths of 4-5 m, it is unlikely that Cladophora beds were exposed to ambient temperatures. It is possible, however, that during the fluctuating flow period from October to January 15, these beds were exposed to greater light intensity as water depth above them decreased. Usher et al. (1987) showed a decline in Cladophora biomass in shallower depths of the Colorado River below Glen Canyon Dam. This correlation between Gammarus and Cladophora may only exist once a critical minimum biomass of algae is surpassed.

The dramatic increase in density of Gammarus lacustris during October 1985 may be attributed to a concentration of amphipods under decreased flows. Prior to this fluctuating flow period, available habitat (i.e., Cladophora beds) for amphipods was much greater. As this available habitat decreased, Gammarus were forced to occupy a smaller area and their standing crop increased. The density of amphipods in March 1986 was more similar to those found under July steady flow conditions and may reflect "normal" densities. With the various flow regimes that occurred during this study it is difficult to determine whether changes in amphipod density were the result of natural seasonal life cycle patterns or the influence of discharge fluctuations from Glen Canyon Dam.

CONCLUSIONS

(1) A significant relationship exists between Gammarus drift and increasing discharges (Figure 1). When flows increase more than 10,000 cfs at one time, there appears to be a threshold at which drift increases. Mean drift rates (number of organisms/hr) and drift densities (number of organism/100 cubic feet of water) for Gammarus lacustris increased during periods of fluctuating discharges.

(2) The most important factor regulating drift was the rising of discharges after periods of low flows. The rate at which discharges rose and fell and the duration of low flows were also important.

(3) Standing crop of Gammarus lacustris in the Colorado River was significantly greater from Glen Canyon Dam to the confluence of the Little Colorado River than below the Little Colorado River.

(4) Standing crop of benthic macroinvertebrates in the Colorado River below Glen Canyon Dam decreased significantly at sites below the confluence of the Little Colorado River.

(5) Dramatic reductions in benthic macroinvertebrates were found in the zone of fluctuation along the margins of the Colorado River.

(6) A significant positive correlation exists for pooled seasonal data between biomass of Cladophora glomerata and standing crop of Gammarus lacustris.

RECOMMENDATIONS

(1) Extreme daily fluctuations from 5,000 to 25,000 cfs, with exposure periods of 12 hours or more, should be avoided. Loss of algal substrate due to desiccation decreases available habitat for benthic macroinvertebrates, thereby reducing fish food base.

(2) Glen Canyon Dam should be operated in such a manner as to approach a seasonal inflow-outflow system with minimal daily fluctuations. This operating criteria should prevent extreme discharge fluctuations and promote algal growth which is important for maintaining invertebrate productivity.

(3) Results of the drift study indicate an increase in drifting Gammarus with rising discharge levels. However, the results are based on limited data and should not be considered conclusive. Additional long-term drift studies should be initiated to determine the impacts of fluctuating discharges over longer periods.

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CLADOPHORA GLOMERATA AND ITS DIATOM EPIPHYTES IN THE COLORADO RIVER THROUGH GLEN AND GRAND CANYONS: DISTRIBUTION AND DESICCATION TOLERANCE

The following is a summary of a 79-page report (Usher et al. 1987) submitted to the Arizona Game and Fish Department. The objectives of the report are to examine the distribution of Cladophora and associated epiphytes in the Colorado River and to determine the role of regulated flow and exposure on each component.

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INTRODUCTION

The Lees Ferry and Glen Canyon Dam tailwater fishery is considered to be one of the Southwest's "blue ribbon" fisheries. For a long time, many have believed that the most important food item in the diets of trout in this fishery was *Gammarus lacustris*, and that *Cladophora glomerata* only provided an important refugium for the *Gammarus*. The occurrence of *Cladophora* in the diets of trout was initially thought to be only incidental to the taking of *Gammarus* (Bancroft and Sylvester 1978). Recently, however, it has been suggested that diatoms epiphytic to *Cladophora* may be providing the trout with a nutritional supplement (Carothers and Minckley 1981).

In light of the potential importance of *Cladophora* and its epiphytic diatoms to the fishery below Glen Canyon Dam, this report attempts to address the following objectives: (1) conduct a thorough literature review of the ecological tolerances of *Cladophora glomerata* and associated epiphytes with regard to those factors potentially significant in regulated rivers (e.g., desiccation, temperature, light, nutrient requirements, and discharge); (2) determine the standing crop of *Cladophora glomerata* along various reaches of the Colorado River through Glen and Grand Canyons; (3) quantify the standing crop and composition of the epiphytic diatom assemblage on *Cladophora glomerata* along the same reaches of the Colorado River; (4) measure the influence of various desiccation regimes on the standing crop of *Cladophora glomerata* in the laboratory; and (5) examine the influence of desiccation on the standing crop and composition of the epiphytic diatoms. For information contained in the literature review we refer the reader to Usher et al. (1987). Additional information can be acquired from an earlier review by Whitton (1970) and the first issue of volume eight (1984) of the Journal of Great Lakes Research, which was entirely devoted to Cladophora in the Great Lakes Region.

For the purpose of this report, the term "steady flows" will be limited to flows that fluctuated less than 5,000 cubic feet per second (cfs) daily. Fluctuating flows will refer, but not be limited to, flows that approach daily fluctuations of approximately 20,000 cfs. A fluctuating flow regime such as this was observed during an experimental release period beginning October 1985 and continuing until January 1986. During this period, high flows ranged from 20,000 to 25,000 cfs and the low flows ranged from 2,000 to 5,000 cfs. Additionally, there was a three-day drawdown during October 1984 that dropped flows from approximately 25,000 cfs to approximately 5,000 cfs. The impacts on the Cladophora during this period are reported along with fluctuating flow data.

METHODS

During the October 1984 drawdown, four collection sites were established. These sites were at 7.5 Mile (below Glen Canyon Dam), Lees Ferry, Paria, and Nankoweap. The zero shoreline was surveyed at the 25,000 cfs water level. Three depth zones at each collection site were established: Cells 1, 2, and 3. Cell 1 extended from the water's edge to 1 ft in depth; Cell 2 ranged from 1-4 ft in depth; and Cell 3 was greater than 4 ft in depth. These cells were stationary and did not move with fluctuating flow; therefore, Cell 1 was dry during much of the fluctuating period of 1985. Random samples of both Cladophora and diatom epiphytes were collected from each accessible cell during each collecting trip.

Lees Ferry and Nankoweap were sampled five times during the study; 7.5 Mile was sampled three times; and the Paria was sampled once. Depth cells at each site were sampled according to river level and accessibility. Northern Arizona University personnel also accompanied the Arizona Game and Fish Department on four river trips: December 1984 and July, October, and December 1985. During these trips, additional sites and depth cells were sampled according to time and accessibility. Taxonomic references used for identification of diatoms included Czarnecki and Blinn

(1977; 1978) and Patrick and Reimer (1966; 1975). At least 200 cells were counted for each estimate.

Experimental studies on the desiccation tolerance of Cladophora were conducted in the lab with Frigid Unit "Living Stream" Systems (Model#LSW-700) as holding tanks. Experiments were conducted on four occasions to provide replicate winter runs (March and April 1985) and replicate summer monsoon runs (July and September 1985). During each test, samples of Cladophora were subjected to four different experimental regimes and a control. These experimental regimes included exposure periods of 12 hours in the dark (night), 12 hours in the light (day), one day and two days. In addition, during the March and September runs, a fifth regime, or three-day exposure period, was included to simulate in the lab the observed field results of the October 1984 drawdown. A study of repeated exposure (i.e., 12-hour exposure followed by 12-hour submergence, repeated over two weeks) was conducted in the stream tank to test the effect of 12- and 24-hour regulated flow cycles. In addition to these experiments, field observations at Lees Ferry also gave some indication of the effects of exposure on Cladophora biomass; in particular, observations during the October 1984 drawdown and the experimental fluctuating flow period in late 1985.

RESULTS

Analysis of Cladophora biomass collected from Cell 1 at eight sites during July 1985 showed a trend of decreasing biomass with distance downstream from Glen Canyon Dam (Figure 1). Sites above the confluence of the Paria River (i.e., Lees Ferry and 7.5 Mile) supported significantly greater Cladophora standing crop than did sites downstream ($T=4.997$, $df=27.1$, $P<.001$). The standing crop observed at Kanab is an anomaly for which there is currently no explanation. A significant depth effect on the standing crop of Cladophora ($F_{2,17}=4.902$, $P<.008$) was also observed. The general pattern during this study was that of an increase in Cladophora biomass with an increase in depth in the river channel.

Analysis of Cladophora standing crop in Cell 2, sampled at Lees Ferry during eight periods throughout the study, showed a significant decrease in biomass following the October 1984 drawdown ($T=4.454$, $df=38.9$, $P<.001$) and the fluctuating flow period at the end of 1985 ($T=9.875$, $df=34.0$, $P<.001$) (Figure 2). The

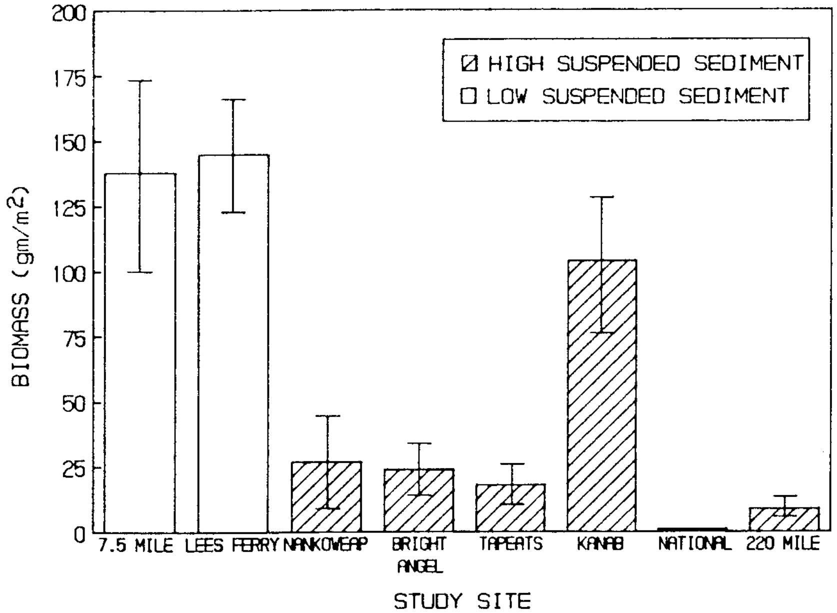

Figure 1. Standing crop of <u>Cladophora glomerata</u> at selected sites, July 1985. Histograms with diagonal hatch lines represent sites with high suspended sediment. Horizontal lines represent +/- one standard error of the mean (s.e.).

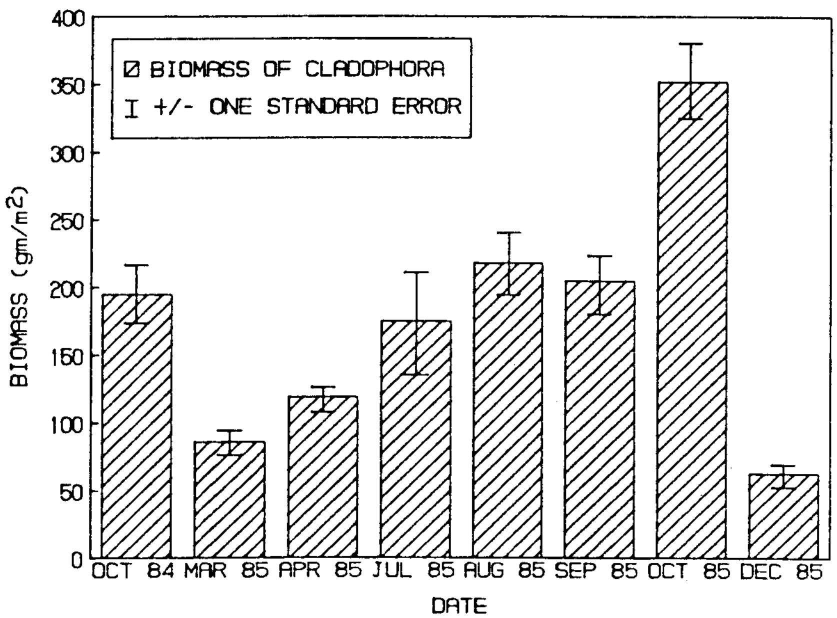

Figure 2. Standing crop of <u>Cladophora glomerata</u> collected at Lees Ferry from October 1984 to December 1985. Notice the significant decrease in March 1985 following the October 1984 drawdown and in December 1985 following a period of fluctuating flows.

apparent effect of the fluctuating flow period at the end of 1985 at Lees Ferry was a reduction in mean standing crop in all cells combined from 303.9 grams/square meter in October 1985 to 113.7 grams/square meter in December 1985. Analysis of biomass in each cell during these two periods showed a significant two-way interaction between cell depth and date of collection ($F_{2,5}=7.978$, $P<.001$). This interaction is shown graphically in Figure 3a-b. In October, the greatest biomass was sampled in Cells 1 and 2; however, following three months of fluctuating flow, Cell 3 had 24 percent more *Cladophora* biomass than Cells 1 and 2 combined. Following this period of fluctuating flow, numerous bleached filaments (presumably nonviable) were .observed in these two cells, which may indicate that the loss of viable *Cladophora* there was greater than the numbers indicate.

During the course of this study, 90 different diatom species were identified as epiphytic to *Cladophora* in the Colorado River below Glen Canyon Dam. Four species were considered co-dominants at the Lees Ferry site. These four species are *Achnanthes affinis*, *Cocconeis pediculus*, *Diatoma vulgare*, and *Rhoicosphenia curvata*. These data agree with the findings of Czarnecki and Blinn (1978). During July of 1985, these four species made up 80 percent of the diatom community at Lees Ferry, but declined in importance with distance downstream from the dam (Figure 4). By River Mile (RM) 220 these species made up only 33 percent of the epiphytic diatom community. Although *Diatoma vulgare* remained a dominant member of the community throughout the system, it still decreased dramatically in density with distance downstream from Glen Canyon Dam.

Two trends were observed in the total density of diatoms epiphytic to *Cladophora*. First, in July of 1985, a significant site effect explaining the distribution of total cell density was observed ($T=6.605$, $df=.5$, $P<.002$). The observed trend shows that the density of diatom epiphytes on *Cladophora* decrease with distance downstream of the dam. Mean total cell density ranged from 629.3 x 10 (7.5 Mile) to 217.7 x 10 (Lees Ferry) cells/cm in Cell 1 above the confluence of the Paria River, and only 92.1 x 10 (RM 220) to 35.0 x 10 (Bright Angel) cells/cm below the confluence.

Second, mean total cell density was significantly affected by depth ($F_{2,23}=3.417$, $P<.038$). This trend, decreasing biomass with depth, was observed at both Lees Ferry and Nankoweap. At Lees Ferry, mean total

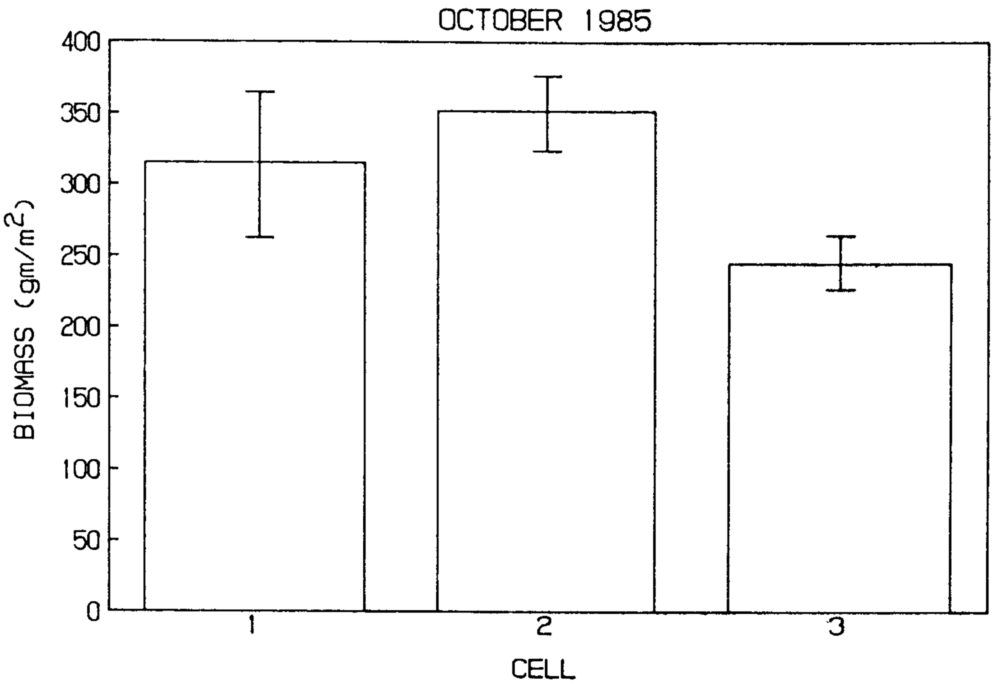

Figure 3a. Standing crop of Cladophora glomerata in depth Cells 1-3 at Lees Ferry in October 1985 following steady flows.

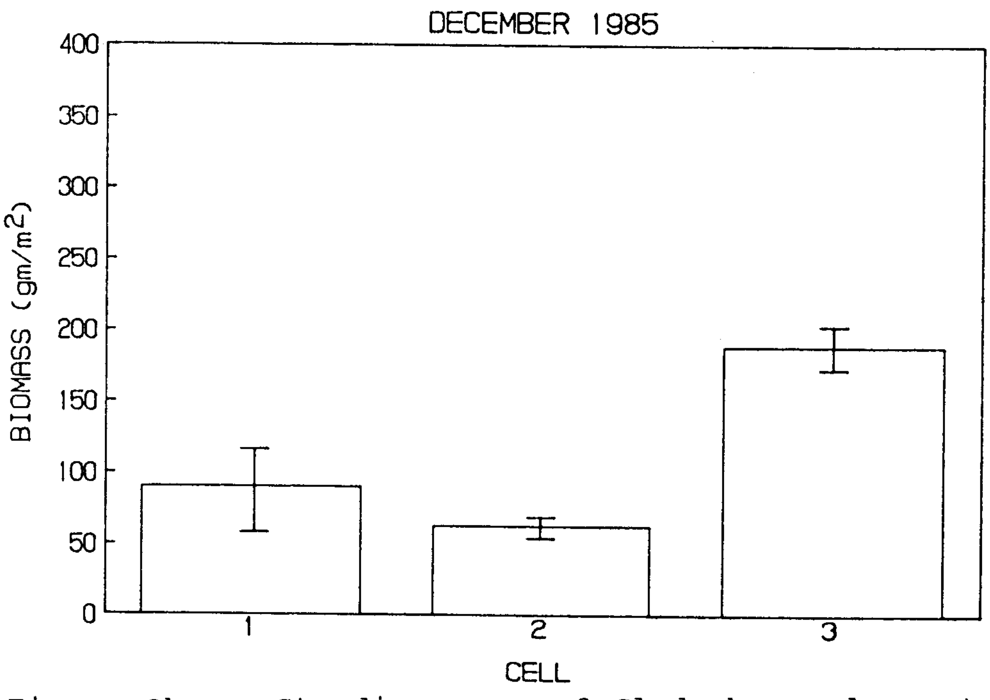

Figure 3b. Standing crop of Cladophora glomerata in depth Cells 1-3 at Lees Ferry in December 1985 following steady flows.

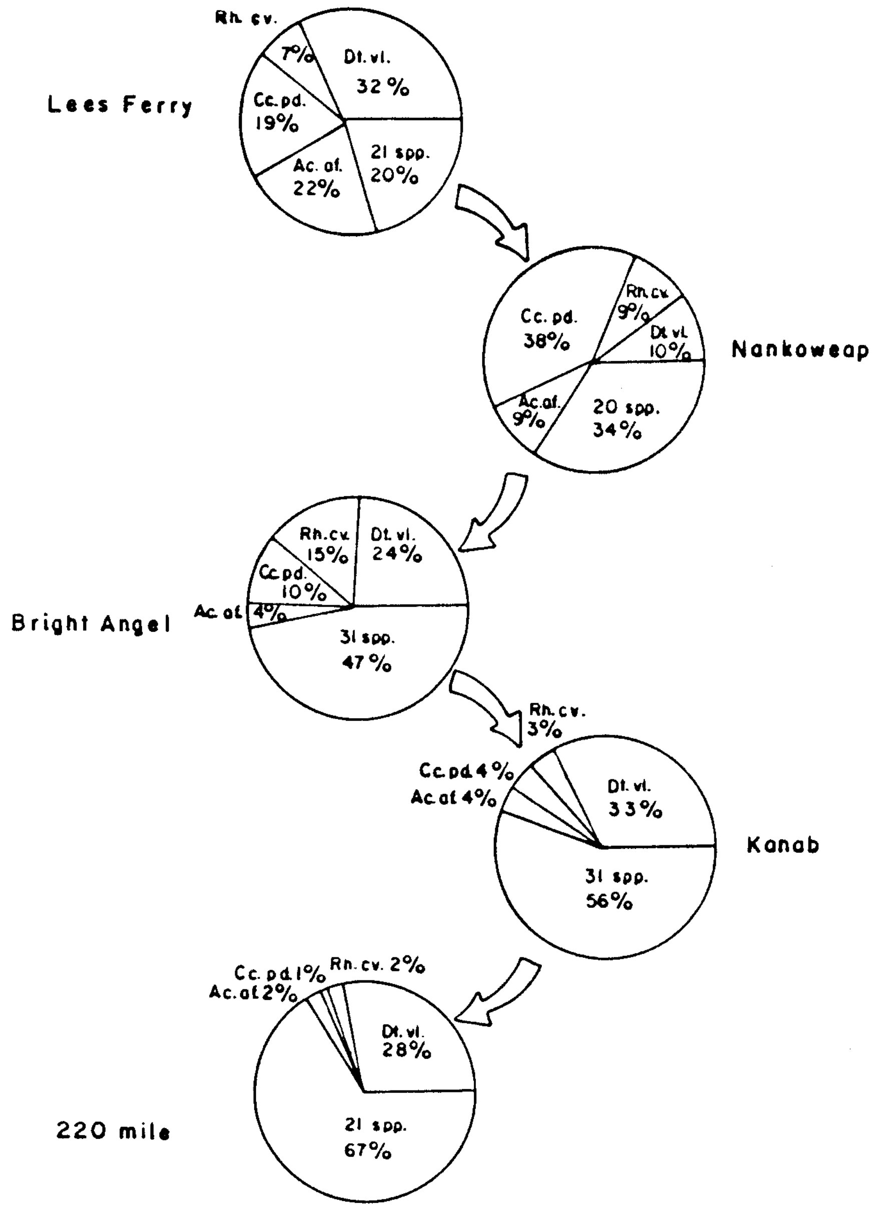

Figure 4. Frequency of the Lees Ferry four co-dominant epiphytic diatoms and remaining diatoms epiphytic to Cladophora glomerata with distance downstream from Glen Canyon Dam. Note the decrease in importance of the four co-dominants at downstream sites. Rh. cv. = Rhoicosphenia curvata, Dt. vl. = Diatoma vulgare, Cc. pd. = Cocconeis pediculus, Ac. af. = Achnanthes affinis.

cell density declined from 302.3 x 10 (Cell 1) to 46.2 x 10 (Cell 3) cells/cm and at Nankoweap from 282.8 x 10 (Cell 1) to 38.0 x 10 (Cell 3) cells/cm. This trend was also observed and found to be statistically significant at Lees Ferry during October and December of 1985 ($F_{2,23}$=21.816, P<.001).

In addition to these trends, a dramatic decrease in mean total cell density of epiphytic diatoms was observed at Lees Ferry between October and December of 1985 during the period of fluctuating flow. The difference in mean cell density from October to December was significant ($F_{1,23}$=65.488, P<.001) (Figure 5). Further analysis indicated a significant three-way interaction between date, depth, and diatom species ($F_{6,23}$=5.402, P<.001), suggesting that each species is affected differently by the fluctuating flows. Of the four dominants at Lees Ferry, Cocconeis, Diatoma, and Rhoicosphenia were virtually eliminated following three months of fluctuating flows. Achnanthes, on the other hand, was not so severely affected and was found in much greater densities after the three months of fluctuating flows than the other three co-dominants. This may be due to the fact that Achnanthes is known as a weedy species that is capable of rapidly colonizing disturbed areas.

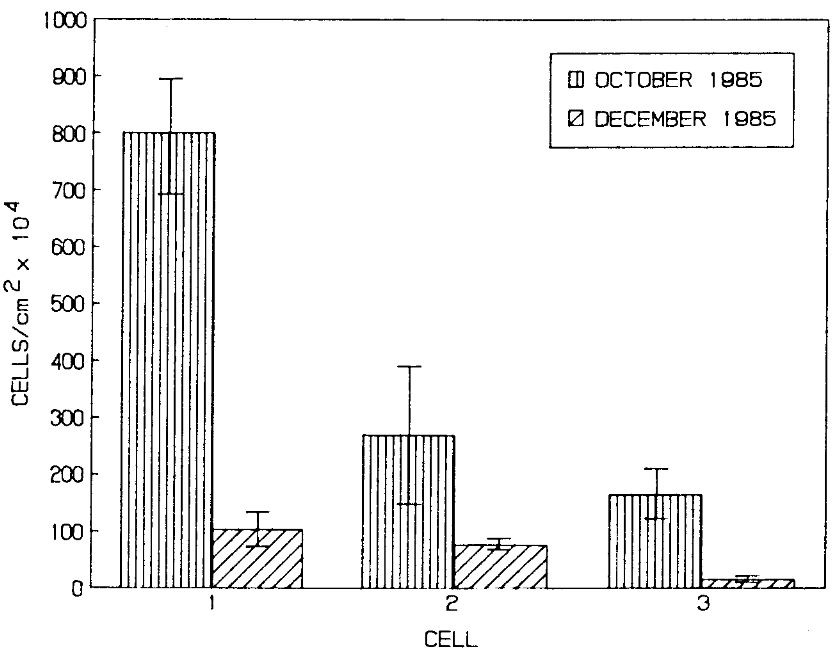

Figure 5. Standing crop of diatoms epiphytic on Cladophora glomerata at Lees Ferry following steady flows (Oct. 1985) and fluctuating flows (Dec. 1985) in depth Cells 1-3.

An analysis of variance was used to test for differences in the results of the laboratory stream tank experiments conducted to determine the effects of regulated flows. There was no significant difference between the two summer monsoon runs ($F_{1,9}=1.67$, $P<.205$). Based on this analysis, the monsoon runs were combined for further study. These desiccation experiments showed that one-time exposures of *Cladophora*, for as little as 12 hours, can result in a reduction of standing crop. Nearly all the exposure periods resulted in reductions of standing crop. The greatest amount of decrease, approximately 84 percent, occurred as a result of the three-day exposure during the Winter 1 trial. Exposures of 12 hours generally resulted in reductions which ranged from 57 percent (Winter 1) to as little as 4 percent (Monsoon) (Figure 6). One exception to this was the unexpected increase in standing crop following the 12-hour night exposure during the Winter 1 test run. The one-day exposures resulted in standing crop decreases ranging from 62 percent (Winter 1) to as little as 25 percent (Winter 2) (Figure 6). Two- and three-day exposures showed results similar to the one-day exposures.

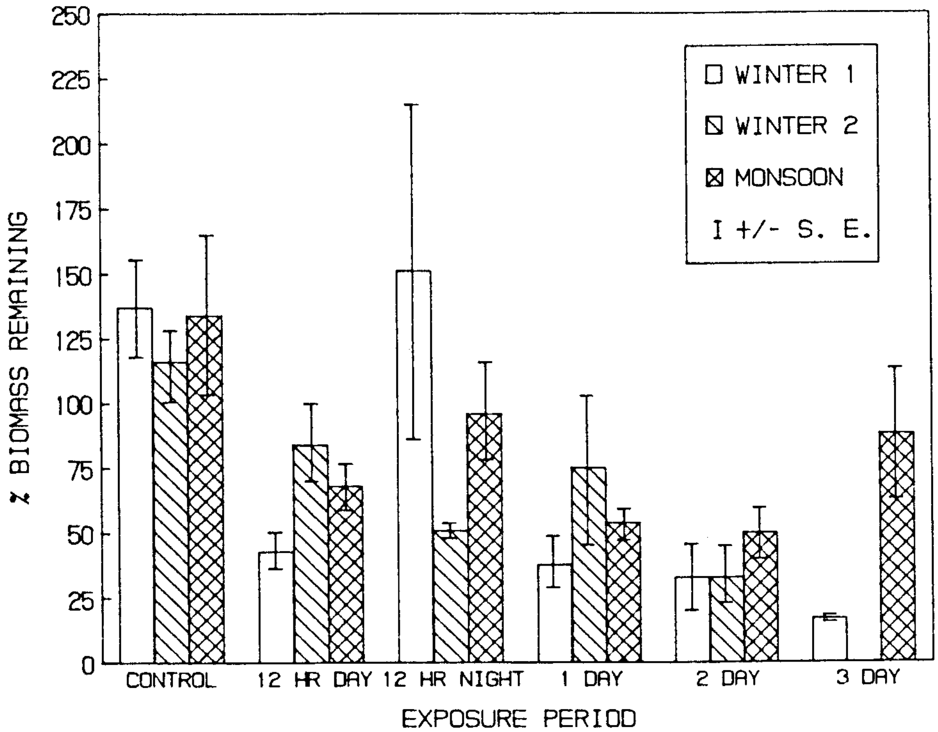

Figure 6. Percent standing crop of *Cladophora glomerata* remaining following experimental trials. After experimental exposures of the indicated duration, the *Cladophora* was rewetted and allowed to incubate for two weeks in a laboratory stream tank.

Statistical analysis of the repeat exposure experiments conducted in the laboratory suggests that repeated exposure of either a 12-hour or 24-hour cycle will have detrimental effects on the standing crop of Cladophora. During the two-week period, exposure resulted in the bleaching of many of the Cladophora filaments. If the bleached filaments are accepted as viable, and included in the measurement of biomass, there is only a 22 percent decrease as a result of the exposures (Figure 7). This decrease is not significantly different from the 5 percent increase in biomass of the control ($F_{2,21}=1.263$, $P<.304$). However, if these bleached filaments are considered dead and only viable green filaments are included in the analysis, then the decrease is as much as 75 percent, which is significantly different from the increase of the control ($F_{2,21}=10.032$, $P<.001$) (Figure 7).

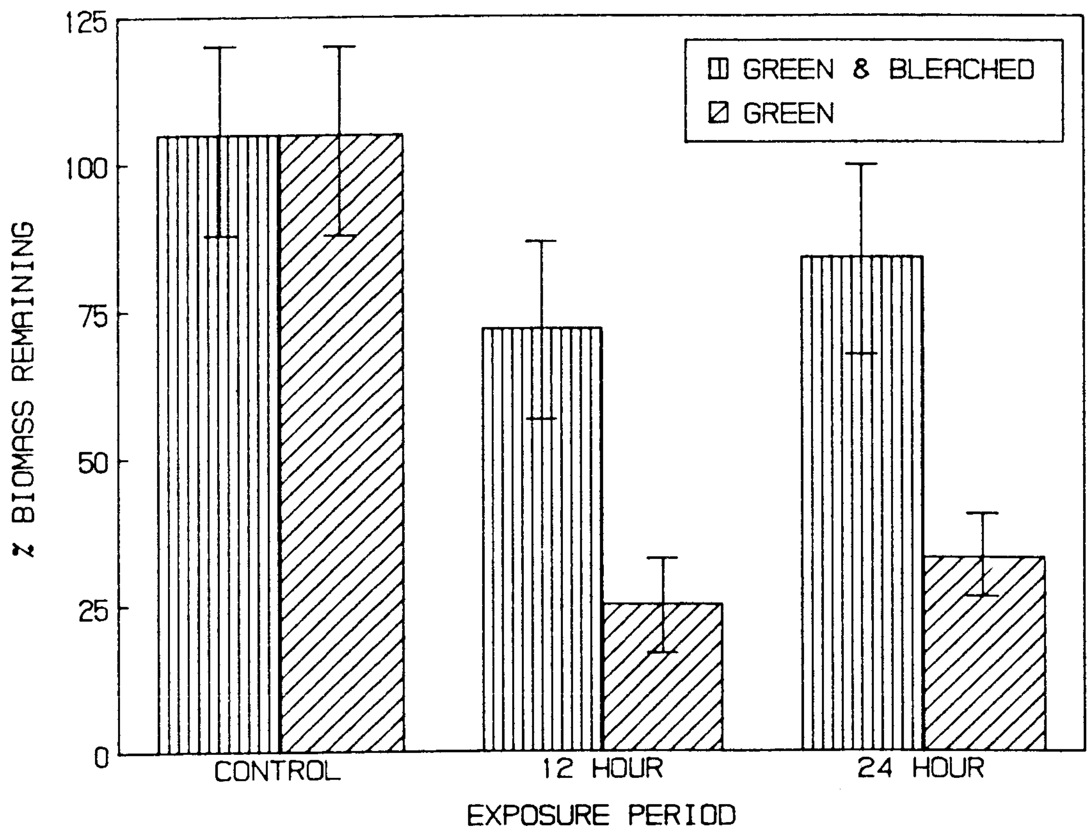

Figure 7. Percent standing crop of Cladophora remaining after a two-week period of intermittent exposure and rewetting. Experimental cycles of 12 and 24 hours were compared to a control which remained wet throughout.

DISCUSSION

The results of this study suggest that daily fluctuations in flow from the bottom of Glen Canyon Dam reduce the standing crop of *Cladophora glomerata* and its epiphytes in the Glen Canyon tailwaters and the Colorado River through Grand Canyon. The effects of exposure were observed in the field and in the laboratory, and in both cases a decrease in biomass was the result.

Distribution of *Cladophora* and its epiphytes following periods of steady flow showed a significant decrease downstream from the dam. In addition, the common diatom epiphytes found on *Cladophora* in the Glen Canyon Dam tailwaters above the confluence of the Paria River showed a continual decrease in importance with distance downstream from the dam. This decrease in biomass and shift in epiphyte dominance is possibly the result of increased silt loads during certain periods of the year below the confluence of the Paria River. The silt has two effects on the *Cladophora* and its epiphytes. First, it physically abrades the algal cells much like a sand blaster. Second, it filters out and decreases the depth at which sufficient light can penetrate for photosynthetic activity.

Cladophora biomass and epiphyte cell density are also affected by depth of the water. *Cladophora* shows a steady increase in biomass with greater depth. Light penetration decreases with depth. The fact that *Cladophora* grows well in the dimly lighted water of the deeper zones supports the work of earlier authors who have suggested that *Cladophora* is adapted to relatively low-light habitats (Adams and Stone 1973; Graham et al. 1982; Hoffman 1979; Neel 1968; Wood 1968). The diatom epiphytes show just the opposite trend: a decrease in cell density with an increase in depth. In addition, species dominance shifts with greater depth of water. *Cocconeis* and *Rhoicosphenia* dominate the shallow water zones and *Diatoma* dominates the deeper water. This may be a function of the degree of habitat disturbance due to flow regulation. *Cocconeis* and *Rhoicosphenia* are firmly attached to *Cladophora* and therefore can withstand a great deal more disturbance than the more loosely attached *Diatoma*.

The effects of desiccation were observed in three ways: (1) in situ following a three-day drawdown to approximately 5,000 cfs during October 1984, (2) in situ following a three-month fluctuating flow period at the end of 1985 with flows ranging from approximately

5,000 to 25,000 cfs, and (3) in the lab with both single and repeated exposures. In every case, a reduction of both Cladophora biomass and epiphyte cell density was observed. In situ observations showed that Cladophora and its epiphytes in the shallow and mid-water zones, which were subjected to the greatest amount of exposure, were most severely impacted.

Based on the laboratory experiments, it was clear that an exposure period of as little as 12 hours could have significant effects. In addition, the effects of one-time exposure differed from that of repeated exposures. Experiments involving repeated desiccations more accurately mimic natural conditions than do one-time desiccation experiments (Hodgson 1981). The repeated experiments showed a much greater decline in Cladophora biomass after two weeks than did the one-time exposure experiments. The extent of loss in both laboratory experiments and in situ observations may have been affected to some extent by the time of year and the immediate meteorological conditions. This assumption is supported by studies of marine intertidal algae (Dring and Brown 1982; Dromgoole 1980; Jones and Norton 1979). The shortest exposure period investigated during our experiments was 12 hours. The effect of this 12-hour exposure varied, depending on time of day and the atmospheric microconditions which the Cladophora was subjected to. During this study, atmospheric conditions were measured qualitatively and therefore the results are difficult to interpret. However, it does appear that freezing temperatures in the winter and slight breezes combined with hot, dry conditions in the summer can result in significant losses of Cladophora during an exposure period of 12 hours. The effect of these atmospheric conditions on Cladophora exposed for shorter periods has not been tested; however, field observations indicate that the basal holdfast can dry in the summer following periods of exposure as short as four hours in duration (pers. obs.). When the river level falls, exposure produces a distinct drying pattern in Cladophora. The damage which follows results in the loss of viable as well as damaged filaments due to drift when the river level rises.

The diatom epiphytes are also reduced as a result of exposure. Initially the tufts of Cladophora that are torn off into the drift may be rich in epiphytes; however, with repeated exposure, the density of diatoms epiphytic to attached Cladophora, as well as drifting Cladophora, may decline. It has been reported that colonization of diatom epiphytes on young, rapidly growing host filaments is uncommon (Kociolek et al. 1983). If any Cladophora survives after repeated exposures, it is likely that the remaining filaments will be of this type. If this is the case, then the habitat may be suboptimal for epiphyte growth, and fewer diatoms could be expected. Our results show that, under steady flows, the epiphytes are most abundant in shallow zones and sharply drop-off in density with depth. These shallow zones are the areas most severely impacted by fluctuating flows. Therefore, the decline in diatom density observed during this study may be the result of damage due to exposure and a reduction in usable habitat. Our data do not suggest that the Cladophora in deep water will be colonized when the shallow water habitat is destroyed.

How will this affect the whole aquatic ecosystem of the Glen Canyon Dam tailwaters and the Colorado River through Grand Canyon? Cladophora and its associated epiphytes are at the base of the aquatic food chain in the Colorado River below Glen Canyon Dam, particularly in Glen Canyon. Cladophora provides an attachment site for epiphytic diatoms. Gammarus feed on Cladophora and attached diatoms (C. Pinney, pers. comm. 1986) and in turn are fed upon by trout. Aquatic insect larvae that are commonly found in Cladophora tufts are another important dietary component for trout and native fish (Carothers and Minckley 1981). If the Colorado River below Glen Canyon Dam is subjected to fluctuating flows similar to those experienced late in 1985 (5,000-25,000 cfs; U.S. Bureau of Reclamation 1985), one might predict a breakdown in the present aquatic ecosystem with potential disruption of the trout and native fish populations of the river. This conclusion is complicated by observations of the status of the Colorado River fishery prior to 1983. At that time, the Colorado River had been subjected to similar fluctuating flow patterns with no apparent detrimental effects to the trout or native fishes.

An important question remains unanswered. The in situ observations of the effects of exposure were carried out during the fall of two consecutive years. Typically, the fall is a time of growth (Bellis and McLarty 1967; Chudyba 1965; Herbst 1969; Manatai 1982; Moore 1976; Wong et al. 1978; Wood 1968); however, during both study periods we observed significant losses of Cladophora. At the present time we have no way of separating the effect of seasonal trends in the growth of Cladophora from the suspected effects of exposure. Although it appears quite clear from both our in situ and laboratory observations that exposure results in significant declines in standing crop of Cladophora, some of the decline may be due to undetected seasonal trends that are contrary to the patterns reported in the literature.

CONCLUSIONS

(1) Standing crop of Cladophora glomerata in the Colorado River above the confluence of the Paria River is significantly greater than in the Colorado River below the confluence.

2) Standing crop of Cladophora glomerata shows a significant increase with increasing depth during steady flow conditions at Lees Ferry.

(3) Density of epiphytic diatoms on Cladophora glomerata in the Colorado River through Glen and Grand Canyons decreases significantly with distance downstream of Glen Canyon Dam.

(4) The density of epiphytic diatoms on Cladophora glomerata decreases significantly with increasing depth during steady flow conditions at Lees Ferry.

(5) Composition of epiphytic diatoms on Cladophora glomerata changes with distance downstream of Glen Canyon Dam. Achnanthes affinisminutissima, Cocconeis pediculus, Diatoma vulgare, and Rhoicosphenia curvata decrease in importance with distance downstream of Glen Canyon Dam.

(6) Laboratory experiments and field observations suggest that exposure and desiccation of Cladophora glomerata and its epiphytes result in a significant decrease of standing crop and cell density.

(7) Depending on local atmospheric conditions, exposures of 12 hours in duration can result in significant reductions in standing crop of Cladophora glomerata.

(8) One-time exposure and repeated cycles of exposure and rewetting both result in a significant decrease in standing crop of Cladophora glomerata. Over a two-week period, a comparison of one-time exposures and repeated cycles of exposure and rewetting showed greater losses following the repeated cycles.

RECOMMENDATIONS

(1) Daily fluctuations from 5,000 cfs to 25,000 cfs, with exposure periods of 12 hours or more, should be avoided.

(2) Investigations of the effects of exposure periods of less than 12 hours in duration should be conducted to determine their impact on the standing crop of *Cladophora glomerata* below Glen Canyon Dam.

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ZOOPLANKTON OF THE COLORADO RIVER,
GLEN CANYON DAM TO DIAMOND CREEK

The distribution and abundance of zooplankton found in the Colorado River between Glen Canyon Dam and Diamond Creek is related to the zooplankton found in Lake Powell, the discharge mode and rate from Glen Canyon Dam, and to habitat types in the river.

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INTRODUCTION

In unregulated rivers, true plankton are found only in the lower reaches or for short distances below natural lakes (Ward and Stanford 1983). With impoundment, the reservoirs contribute lentic plankton to the river below the dam; other plankton come from the bed, backwaters, and tributaries of the river below the dam (Petts 1984). Three interacting factors should be important in controlling zooplankton in the Colorado River: (1) the distribution and abundance of plankton in Lake Powell, (2) the characteristics of the Glen Canyon Dam discharge regime, and (3) the transport and survival of plankton in the river below the dam.

Glen Canyon Dam, under normal operating conditions, is a hypolimnial release reservoir with penstock intakes at a full pool depth of 70 m. Other release modes are from the jet tube intakes (100 m depth) and the surface withdrawal spillways. As lentic plankton occur throughout these depth ranges, and have depth preferences depending on species, growth stage, season, time of day, etc. (Hutchinson 1967), the discharge mode from Lake Powell will affect the type and numbers of plankton released to the river. The release rate will also affect both the withdrawal patterns of zooplankton from the lake and the survival of plankton in the tailwaters and below through interactions of river flow with refuges, severity of the rapids, and frequency and structure of backwaters.

METHODS

The plankton collections used to prepare this report are summarized in Table 1. The only other study of the plankton of this part of the River (Cole and Kubly 1977) did not report quantitative data, mainstream sampling locations, or dates of collections. All samples reported here were taken with plankton nets (Table 1). Various techniques of net deployment were used, including surface and repetitive oblique tows from boats, collections from riverbanks, and casting and retrieving nets across terminal pools. Samples above Glen Canyon Dam integrated depths to 15 m or 30 m; no depth stratified information from the lake adjacent to the dam is available. A flow meter was used whenever possible to derive water volume filtered. Some volumes were calculated from stream velocity and time the net was in the water or from the length of tow alone. A number of samples were nonquantitative.

Table 1. Summary of zooplankton collections from the Colorado River and above Glen Canyon Dam used in this report.

Date	Number of Samples	River Miles (inclusive)	Nets Used Diam (cm)	Nets Used Mesh (μm)
		Colorado River		
6/19/80 - 7/1/80	19	20 to 223	30	212
			30	363
12/30/80 - 1/1/81	5	-15 to -12	30	363
8/2/84	2	43	13	80
12/19/84 -1/17/85	10	-15 to 185	13	80
			13	243
10/7/85 -10/14/85	6	28 to 194	13	80
11/10/85-11/22/85	14	0 to 132	13	80
		Lake Powell at Glen Canyon Dam		
6/25/81	2	-	30	363
11/8/82-11/12/82	2	-	30	363
8/24/83	1	-	13	243
7/27/84	4	-	13	243
1/14/85	1	-	13	243

Adult crustaceans were identified using Pennak (1978) and Ward and Whipple (1959). Harpacticoid, calanoid, and cyclopoid copepod nauplii were lumped as one category, while immature (copepodid) stages were listed separately. Egg-bearing female copepods and male copepods with internal spermatophores were counted. Crustaceans in poor condition (parasitized by fungus or protists, internal body structures partially or completely lacking, damage due to decay) were noted.

Because of the diversity in sampling gear and methods, the restricted number of collection sites and samples, and the high variability of planktonic systems, no extensive statistical analyses of the data were undertaken.

RESULTS AND DISCUSSION

LAKE POWELL ABOVE GLEN CANYON DAM. The seasonal cycle of abundance and composition of zooplankton in Lake Powell adjacent to the dam is shown in Figure 1. Total abundance varied by about two orders of magnitude from a low in late fall to a late summer peak. Cladocerans were dominant in three of the five sampling periods. Extreme changes in species composition occurred within taxonomic categories: the June 1981 cladoceran fraction was almost all *Daphnia pulex*, while the August 1983 cladocerans were mostly *Diaphanosoma birgei*. Similar variations occurred within the calanoid copepod fraction. The cyclopoid copepods were always dominated by *Diacyclops thomasi*.

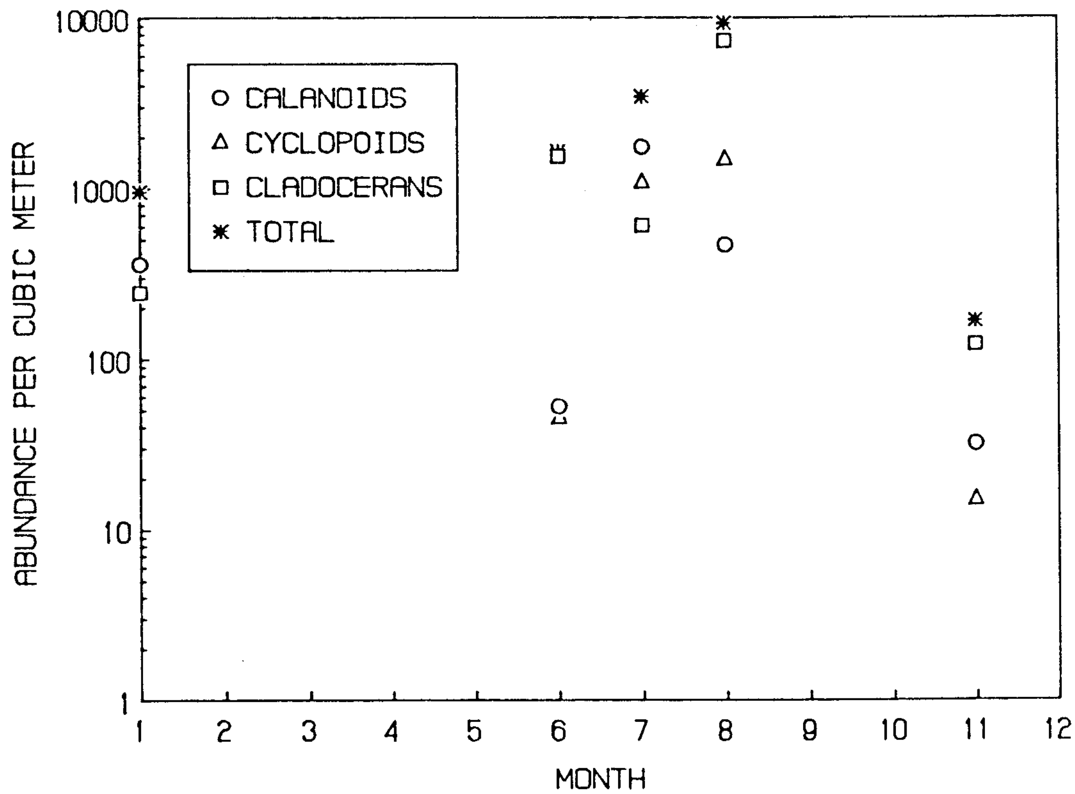

Figure 1. The seasonal cycle of abundance of zooplankton in Lake Powell adjacent to Glen Canyon Dam.

The seasonal variations in abundance and taxonomic composition in Lake Powell should be reflected in the plankton found below the dam, with additional shorter time-scale variations introduced by variations in discharge rate resulting from changes in withdrawal current structure, depth of release, and the interaction of the depth of release with the depth of organisms which undergo diel vertical migration. Since nothing is known about species depth distribution in Lake Powell, no inferences can be drawn at this time. Clearly, an important objective of future work should be to obtain this information so that discharge effects can be identified and models developed to predict them.

COLORADO RIVER: GLEN CANYON DAM TO DIAMOND CREEK.

(1) COMPOSITION. Table 2 summarizes the crustacean species known or potentially able to be present in the plankton. Calanoid copepods occurred in the highest percentage in all samples except the November 1985 collections, when cyclopoids were dominant. Cladocerans were always the least abundant except during the summer of 1980, when high spillway releases occurred. In terms of species, dominant calanoids were Skistodiaptomus pallidus and Leptodiaptomus ashlandi; Diacyclops thomasi was always the dominant cyclopoid, and Daphnia galeata the dominant cladoceran. These are usually the numerically important species in Lake Powell. No relationship between distance downriver and proportions of taxa was apparent in the data.

(2) ABUNDANCE. In none of the individual sample sets was there clear evidence of a decrease in abundance of any taxonomic category or species with distance below Glen Canyon Dam. Figure 2 summarizes this result. The lack of a relationship between abundance and distance was not expected (see Hynes 1970). The sampling program allowed no direct comparison of main channel abundance with potential refuges or other sources of supply to the river that might be independent of the Lake Powell contribution. There is evidence (see below) that Lake Powell plankton survives the passage to Diamond Creek with only small mortality. If true, then Lake Powell zooplankton discharges could interact with endemic resources (e.g., benthic invertebrates, fish spawning, and nursery areas) throughout the length of the river to Lake Mead.

There was no relationship between abundance and release rates from Glen Canyon Dam except during the high June 1980 releases (which included high spillway

Table 2. Crustaceans found in the Colorado River and its tributary terminal pools between Glen Canyon Dam and Diamond Creek. Asterisks denote true plankton; the remainder are benthic and are only occasionally found in the plankton.

COPEPODS

Calanoids*	Cyclopoids
Aglaodiaptomus clavipes	Acanthocyclops vernalis*
Aglaodioptomus forbesi	Diacyclops thomasi*
Leptodiaptomus ashlandi	Eucyclops agilis
Leptodiaptomus sicilis?	Eucyclops speratus
Skistodiaptomus pallidus	Mesocyclops edax*
Skistodiaptomus reighardi	Paracyclops fimbriatus poppei
	Tropocyclops prasinus mexicanus*

CLADOCERANS	AMPHIPODS
Alona affinis	Gammarus lacustris
Alona guttata	
Bosmina longirostris*	OSTRACODS
Chydorus sphaericus*	Cypridopsis vidua
Daphnia galeata mendotae*	Cyprinotus incongruens
Daphnia parvula*	Cyprinotus pellucidus
Daphnia pulex*	Cyprinotus salinus
Diaphanosoma birgei*	Herpetocypris reptans
Leydigia quadrangularis	Ilyocypris bradyii
Pleuroxis aduncus	Paracandona euplectella
Pleuroxis denticulatus	Potamocypris sp.

discharges). To look for diel changes in abundance,five samples were taken over a 20-hour period above Hance Rapids (River Mile [RM] 72) in November 1985 when dam discharge varied from 6,000 to 18,000 cubic feet per second (cfs). The cycle of abundance observed may be related to the discharge rate (affecting entrainment levels at the intakes), to the day-night cycle of light affecting abundance, or may be fortuitous, given the high variability of plankton samples. Species proportions remained relatively constant over the 20 hours of sampling.

Non-crustacean invertebrate drift, although not quantified, appeared to be less important numerically than the true zooplankton, although it probably contributed the major fraction of the biomass being carried downstream. Drift was less important in backeddies and terminal pools.

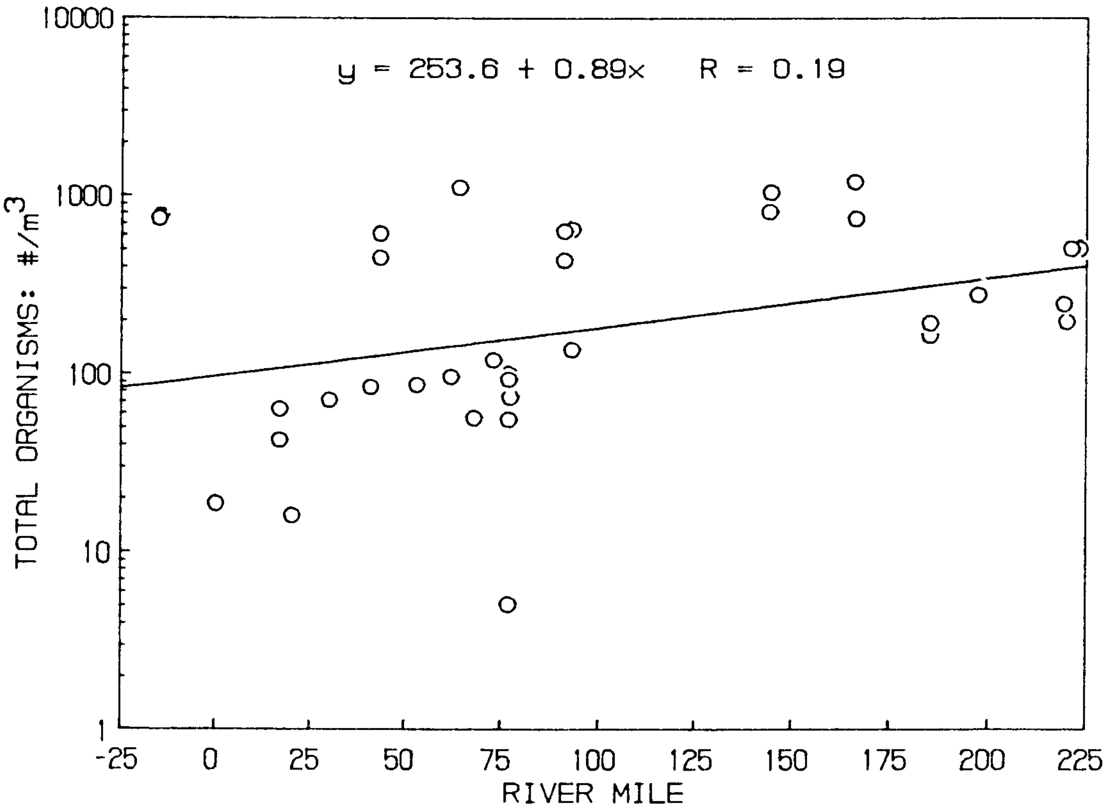

Figure 2. Abundance of plankton as a function of river mile. Data from all collections.

(3) CONDITION. While no decrease in abundance was apparent in the data, a significant change in condition with river mile was noted. Figure 3 summarizes all copepod data. As much as 25 percent of the total number of copepods found near Diamond Creek could be in poor condition.

(4) REPRODUCTION. Egg-bearing females and male copepods with spermatophores ready for extrusion were found throughout the river on all sampling trips. There were high abundances of naupliar stages in some samples, indicating survival in Lake Powell releases and possible hatching of eggs from river populations. Whether the reproductive activity observed occurs solely among Lake Powell discharged plankton or is a product of losses from endemic or refuge population is not known.

(5) ENDEMIC AND REFUGE POPULATIONS. Comparisons between main channel populations and potential resident populations in backwaters and terminal pools were made in June 1980. The exchange rate appears to be high, at

least under the release conditions (40,000+ cfs) during sampling. This was inferred from the agreement in percentage of females carrying eggs and of animals in poor condition between the mainstream and possible refuges. Thus, high releases appear to reduce the residence time of water (and organisms not able to counter the flow) to a point where no difference in copepod population structure can be detected. At lower flows, barriers to exchange or longer residence times in eddies may permit persistent populations to develop. Fluctuating flows and their unpredictable effects on barriers and exchange rates, coupled with naturally occurring episodic high flows, should make it difficult to estimate the importance of these populations.

(6) ZOOPLANKTON AND FISH. The gut content studies of the Arizona Game and Fish Department showed that first-feeding and older larvae of rainbow trout and bluehead and flannelmouth suckers take zooplankton. Larvae of other native and introduced fish should also feed on zooplankton (Minckley 1973). Adult speckled dace (Rhinichthys osculus), collected during June 1980 above Tanner Rapid (RM 68.5) and in the Kanab Creek (RM 143.5) terminal pool, had no zooplankton in their guts.

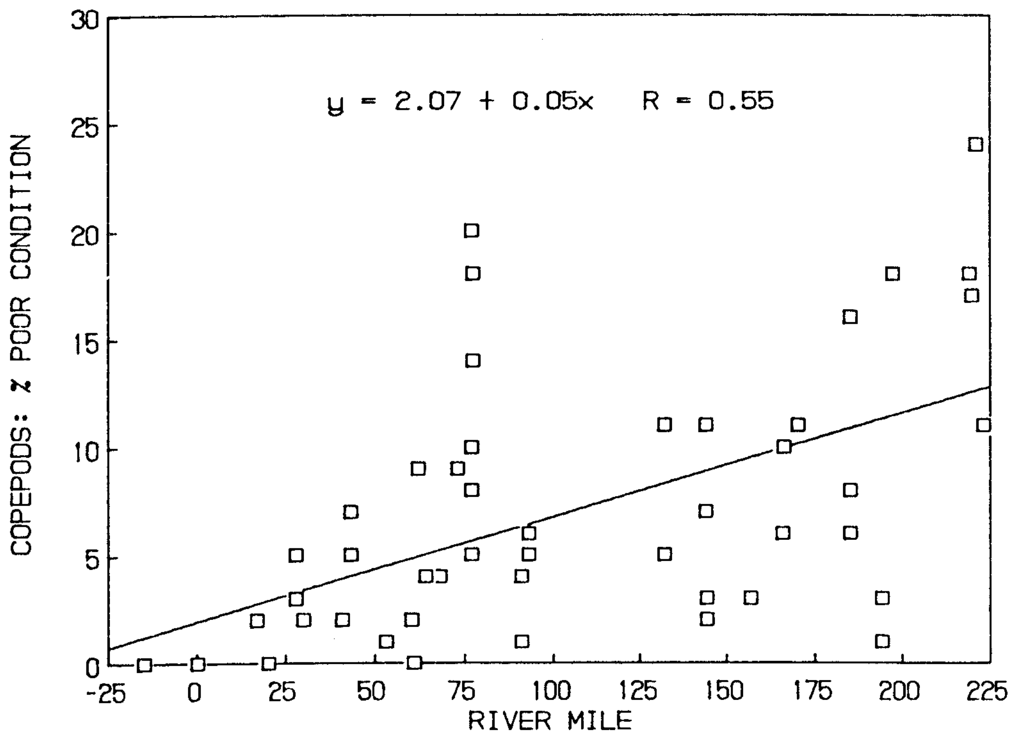

Figure 3. Percent copepods in poor condition plotted against river mile. Data from all collections.

Hynes (1970) discussed the importance of zooplankton released from reservoirs to the establishment and maintenance of large benthic invertebrate populations below dams. It is not known whether this relationship exists below Glen Canyon Dam; but if it does, and assuming the benthic invertebrates and their drift are important food for larval and adult fish, then the fishes of the river are indirectly tied to the status of the zooplankton.

The input of Lake Powell zooplankton dependent on dam release mode could provide a means of increasing food to larval fish in the river, especially to the trout populations in the dam to Lees Ferry reach. Spillway releases at night would draw the highest abundances (both copepod and cladoceran) from the lake. High discharge rates, however, from any release mode might have a detrimental effect on the tailwater populations because of the possibility of washout from the area immediately below the dam.

CONCLUSIONS

Of the 33 species of crustaceans that have been found in the Colorado River between Glen Canyon Dam and Diamond Creek, 16 are true members of the plankton; the remainder are normally benthic and found in the plankton as drift. Lake Powell is the source of most or all of the true zooplankton found in the river. Since little is known about seasonal cycles of abundance and year-to-year variability, and nothing about depth distributions of the lake zooplankton, the initial conditions of zooplankton introduced to the river cannot be predicted as a function of yearly and seasonal release demands or daily dam discharge mode.

Although drift invertebrates are usually less abundant than zooplankton, they probably constitute the largest fraction of the total invertebrate biomass transported down the river. There is no information on the quantitative aspects of invertebrate drift in the Colorado River.

The abundance of crustacean zooplankton does not decrease with distance downriver from Glen Canyon Dam, although there is a significant increase in the fraction of the population in poor condition. Backeddies, backwaters, and terminal pools, all of which can contain abundant zooplankton, may act as refuges for persistent or endemic reproducing populations that contribute to the downriver transport. Some data, however, suggest that exchange rates between these areas and the river are high, at least at higher flows, so separate populations may not be important under many conditions. Larvae and reproductively-active adults have been found in all environments on the river, so the potential exists for the establishment of viable populations throughout the river to Lake Mead under proper conditions. Backwaters and terminal pools will be the most likely areas populated, but it is not known what flow regimes will permit this to occur.

The zooplankton of the river is dominated by copepods, with calanoids usually more abundant than cyclopoids. Cladocerans were least abundant except for one sampling period when spillway releases made a significant contribution to the total flow of the river. The depth of water release from Lake Powell (penstocks, jet tubes, spillways) should have an important effect on species composition and abundance. The volume of water discharged, which determines the depth of entrainment, will also have an effect. No clear relationship, however, between release rate from the dam and abundance and composition could be established because of limited sampling and dam release modes during the study.

Larval trout and bluehead and flannelmouth suckers feed on zooplankton; other larval fish species should also utilize zooplankton. Adult speckled dace, potential zooplankton predators, in two sets of samples were not feeding on plankton. The lack of information on benthic invertebrates and their drift, and on aquatic food chains, makes it difficult to assess whether the zooplankton-benthic invertebrate-larval/adult fish links are important and how they might be affected by dam operations.

Studies with the following objectives are needed to adequately address the question of how to minimize the impacts of dam operations:

(1) Describe the seasonal cycle of zooplankton species composition, abundance, reproduction, and vertical distribution in Lake Powell adjacent to Glen Canyon Dam.

(2) Develop a model of the interaction of lake zooplankton distributions with withdrawal currents as a function of intake type and discharge rate in order to predict the kinds and amounts of zooplankton introduced to the tailwaters.

(3) Quantify the invertebrate drift in the river and its tributaries as a function of season, time of day, and river flow.

(4) Determine if the zooplankton-benthic invertebrate-larval/adult fish links in the food chain are important.

(5) Establish if persistent populations of zooplankton exist in refuges independent of populations transported down the river and how such refuges are affected by exchange rates between them and the mainstream.

RECOMMENDATIONS

The following comments are based on the limited data available. The studies suggested above are essential to complete understanding of the consequences of dam operations on the lake-river system.

Monthly baseloaded (i.e., steady) flows are probably the ideal mode for encouraging development of resident zooplankton populations in terminal pools, backeddies, and backwaters by reducing the exchange rate between these areas to a minimum. Periodic (biweekly, monthly?) high flow rates, especially from spillways, might be valuable in recharging these populations.

The prime concern with extreme fluctuating flows is the washout of populations in refuges and possible interference with feeding types/habits involved in the fish-invertebrate-zooplankton links. Long daily periods of low flows would also result in a net reduction of habitat where benthic invertebrates and plankton could survive. Extended exposure to desiccation of sessile organisms, loss of habitat, and increased predation through concentration of mobile organisms into smaller refuges should decrease standing stocks of most organisms. It is possible that the high penstock releases would entrain more water from a shallower depth in Lake Powell, and thus increase the abundance of plankton for short periods. Conversely, the low releases might reduce the numbers delivered to the river through deeper entrainment, and a net decrease in total biomass introduced to the river could result.

The shift between extreme fluctuating flows and steady releases might create a long-lasting transition period of hydrology and sediment redistribution that would result in persistent unstable conditions in terminal pools and backwaters that would be detrimental to planktonic and benthic invertebrates, as well as to fish survival and reproduction. The unstable conditions during this period, perhaps amplified by summer runoff episodes, would almost certainly have a negative effect on the river ecology.

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EVALUATION OF RIPARIAN VEGETATION TRENDS IN THE GRAND CANYON USING MULTITEMPORAL REMOTE SENSING TECHNIQUES

This study examines and quantifies vegetation trends in the New High Water Zone (NHWZ) and Old High Water Zone (OHWZ) riparian areas of selected sites in the Grand Canyon. Aerial photographs from 1965, 1973, 1980, and 1985 have been interpreted for vegetation and digitized into a data base. Acreage statistics are reported by river mile.

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INTRODUCTION

The Colorado River riparian habitat in Grand Canyon National Park has changed during the last 23 years as a result of the installation of Glen Canyon Dam. Fluctuating flows from the dam's peaking power operation determine water elevations in the canyon. Controlled water regimes have reduced flooding and have dictated new areas of riparian habitat. Since 1963, many investigators have reported these changes. Turner and Karpiscak (1980), by comparing oblique photographs, noted that the most obvious vegetation change has been the increased density of New High Water Zone (riverside) species. Carothers and Aitchison (1976) found that the construction of Glen Canyon Dam has permitted the development of a new riparian community typically characterized by tamarisk, arrowweed, coyote willow, desert broom, and seep-willow. Johnson et al. (1976) noted similar changes.

METHODS

In June 1983, the Glen Canyon Environmental Studies (GCES) Team asked the U.S. Bureau of Reclamation's Remote Sensing Section to conduct a pilot project designed to quantify these changes. One raft trip in September 1983 was conducted to gather ground reference information, which was then interpreted, digitized, and analyzed by computer.

Upon completion of this preliminary work, it was decided to study seven sites, each approximately 3 miles in length, by comparing sets of aerial photographs from four different years. Later in the study, an eighth site above Lees Ferry was added. The dates of pre-existing photographs were May 1965 (black and white), June 1973 (black and white), and July 1980 (color infrared). The fourth set was made up of color infrared photographs taken under contract from the U.S. Bureau of Reclamation, Salt Lake City Office, in June 1985. Scales of photography varied: 1965=1:12,000; 1973=1:7,200; 1980=1:4,800 to 1:3,600; and 1985=1:4,800. Existing color photographs from 1979 at a scale of 1:3,000 were also used for the site above Lees Ferry.

The vegetation was interpreted in two major associations: (1) the New High Water Zone (NHWZ) vegetation, which was essentially introduced after the installation of Glen Canyon Dam, and (2) the Old High Water Zone (OHWZ) vegetation, which marks the old historical flood line. The major plant species in the NHWZ are: seep-willow and desert broom (Baccharis spp.), willows (Salix spp.), tamarisk (Tamarix chinensis), and arrowweed (Tessaria sericea). The major plant species in the OHWZ consist of Apache Plume (Fallugia paradoxa), redbud (Cercis occidentalis), hackberry (Celtis reticulata), honey mesquite (Prosopis glandulosa var. torreyanna), acacia (Acacia greggii), and in the lower reaches of the canyon, creosote bush (Larrea divaricata). It should be noted that these are the major species included in the interpretation, but they are by no means the only species present. Upon gathering ground reference information, additional vegetation was noted, including grasses, forbs, vines, brittlebush, cacti, ocotillo, mormon tea, camelthorn, thistle, and marsh plants such as cattails.

The eight sites chosen for this study are located by River Mile (RM) in the list below:

Site	Approximate River Mile	Site Name
1	(-)9-14 (above Lees Ferry)	Duck Island
2	44-47	Saddle Canyon
3	70-73	Cardenas
4	106-109	Bass Canyon
5	120-123	Blacktail/Forster Canyons
6	166-169	National Canyon
7	207-209	Granite Park
8	219-221	Granite Springs Canyon

River miles in the Grand Canyon begin with RM 0 at Lees Ferry (about 15 miles below Glen Canyon Dam, Arizona) and continue to Pierce Ferry, RM 280, in Lake Mead, Arizona (Figure 1).

Study site locations are areas of interest selected nonrandomly by the U.S. National Park Service in conjunction with the GCES Biological Study Group. Sites were selected because of their importance to wildlife and visitor use and for ease of access to gather ground reference data.

Upon developing the interpretation criteria, work began by classifying vegetation categories and preparing map bases for digitization. A raft trip for gathering reference information to facilitate the interpretation of photographic data was taken in April 1984. In most cases, NHWZ and OHWZ categories were easily distinguishable in the photographs by using Dietzgen portable stereoscopes. However, in some cases where vegetation from the two zones overlapped, ground truth information was invaluable.

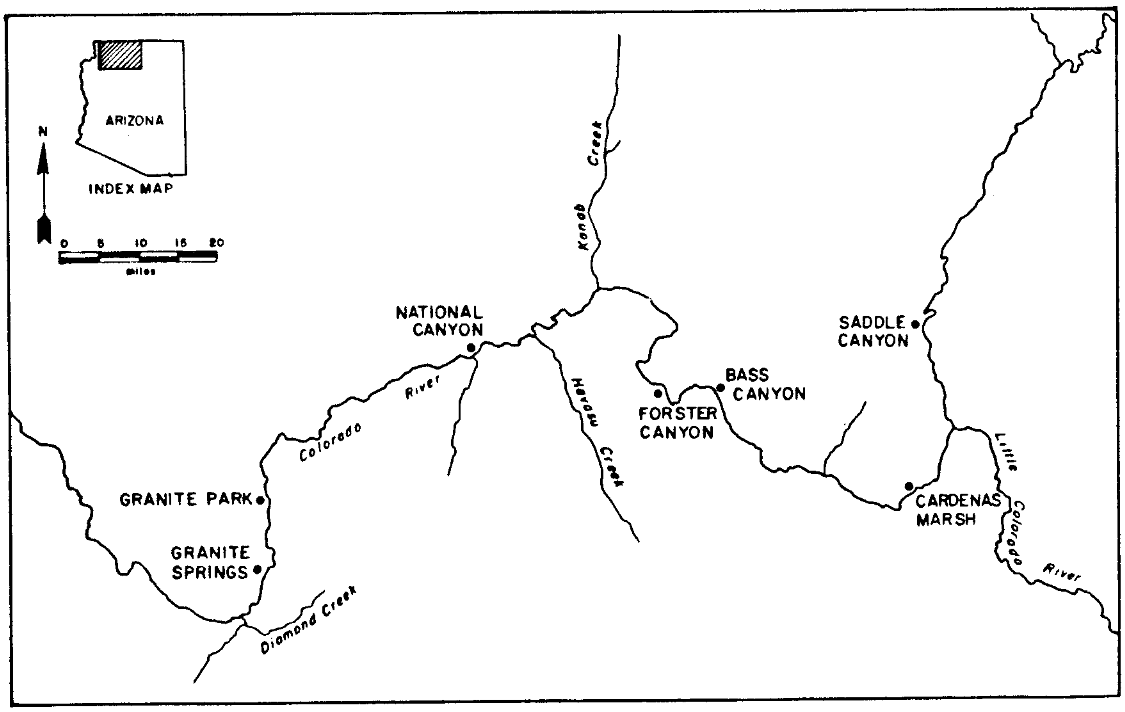

Figure 1. Map of the Colorado River through Grand Canyon National Park with location of study sites.

Vegetation polygons were drawn on transparent mylar sheets overlaid on the photographs. The interpreter then applied densities to the polygons by making comparisons to a density scale, which he viewed as he examined the photographs in stereo. Categories of 20, 40, 60, 80, and 100 percent density were applied to polygons in both NHWZ and OHWZ situations. This facilitated comparisons of actual vegetation changes among photographs. Upon completion of this task, photographic mosaics were made of each river reach.

Normally, the polygon data would then have been transferred to map bases; however, 7.5-minute U.S. Geological Survey (USGS) quadrangle maps were unavailable for most areas of the Grand Canyon. For this work, the scale of the available maps, 15-minute quadrangle sheets (1:62,500), was too small. Our mapping resolutions, in some cases 9-m^2 polygons, were too detailed to transfer accurately onto a 1:62,500 quadrangle map base. We therefore made pseudo-UTM (Universal Transverse Mercator) grids to the scale of the 1980 photographs (1:4,800). These photographs were chosen because they contained the most detail, and because the planned 1985 photography was to be flown at this scale. Our procedure meant that the data would be digitized on an arbitrary UTM grid not referenced to ground coordinates. However, it would be to scale for accurate vegetation acreage tabulation.

In order to match four dates of photography on one grid, a control point file was built. Reference points, usually rocks but sometimes bushes, were selected from each set of photographs. With this method, the river corridor's vegetation could be mapped using multitemporal data sets and then be digitized into our Geographic Information System (GIS) for an accurate trend analysis. By definition, a GIS is a system in which information associated with the land referenced by geographic coordinates is entered and stored by a digital computer for later retrieval, analysis, display, and outputs to aid in the making of modern resource decisions (Koeln and Cook 1984).

We are aware of minor scale differences, photodistortion, and mosaicing problems. However, we believe this is the best way to digitize and prepare vegetation overlays when proper base maps are not available. Since this project was initiated, efforts by the USGS to map the Grand Canyon in 7.5-minute maps have begun and are scheduled for completion in 1988. Any future work on this project could be referenced by these maps. Another method for geo-referencing the data could be to use modern aerial photogrammetry, which is accurate, although very expensive.

River miles (according to Buzz Belknap's Grand Canyon River Guide) were then digitized into the data base for reporting acreage statistics. The product of the digitizing effort is area tabular listings of vegetation in the NHWZ and the OHWZ, with densities applied referenced by date and river mile. Successional trends in the form of graphs were then developed (Figure 2a-b).

The digitization was accomplished by in-house contracting personnel, using a Calcomp 9000 table linked to a Tektronix 4014-13 display screen. This system is run by the Interactive Digital Image Manipulation Software package and a HP-3000 Computer system that is fully dedicated to remote sensing and GIS functions. Digitization was done in vector format. This is point and line data. After digitization, computer functions ALLCOORD, TRNSFORM, STRATA, and BLDSTRAT were run to transform these data into a raster format to facilitate image processing and data manipulation. Rasterized data are essentially in image format.

We then applied density values, reported acreage totals by river miles, and stratified out the 1965 subsets. Initially, our plans were to apply a high water mask to all sets of photographs, believing this would better enable the comparing of multitemporal data, as water elevations fluctuate with the operations of Glen Canyon Dam. As previously discussed, the registration process uses a control point file. The points selected are in a collinear fashion dictated by the river reaches chosen. This gives a poor distribution of control points with a transformation of lesser order than desired. The water mask of one set of photographs did not fit properly when applied to another and was therefore not used in this analysis. However, it should be noted that when the water mask application was attempted on the Saddle Canyon area, it was determined that the 1980 high water image (+33,000 cubic feet per second [cfs]) inundated small amounts of vegetation, but some large shrubs protruded above the water and were therefore tabulated in the 1980 statistics. Applying this water mask to the 1973 data incorrectly assumes that all vegetation under water will not be tabulated. In conclusion, when comparing four dates of vegetation in a river environment as we did in our study, water elevations should normally be considered. However, because our analysis lacked proper base maps, the data would have been improperly biased had we done so.

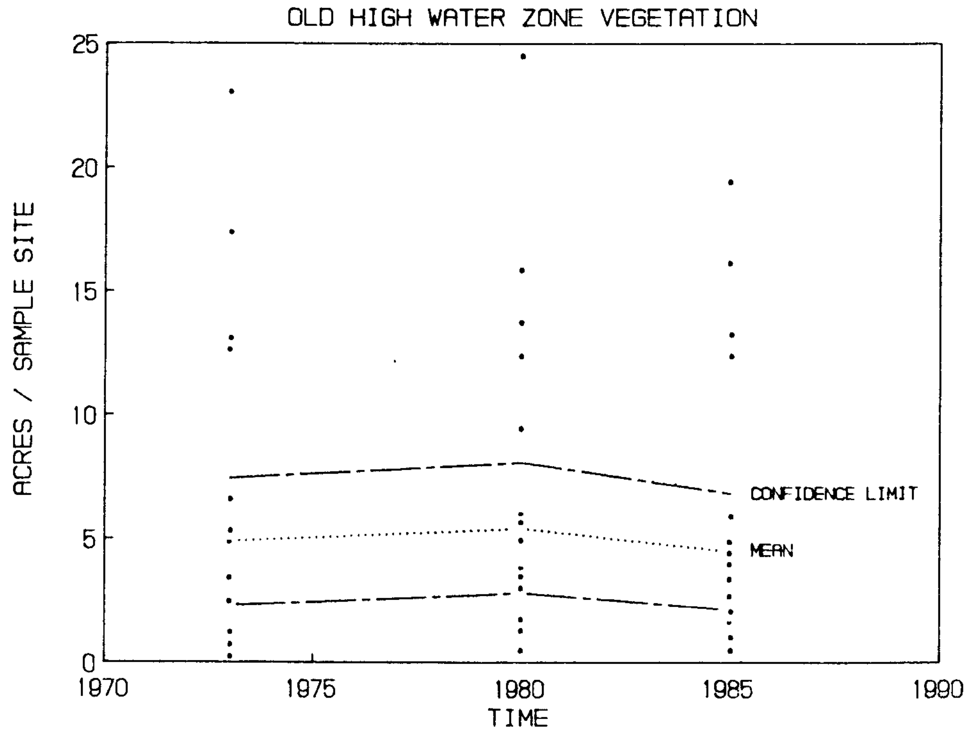

Figure 2a. Vegetation cover trends in the Old High Water Zone.

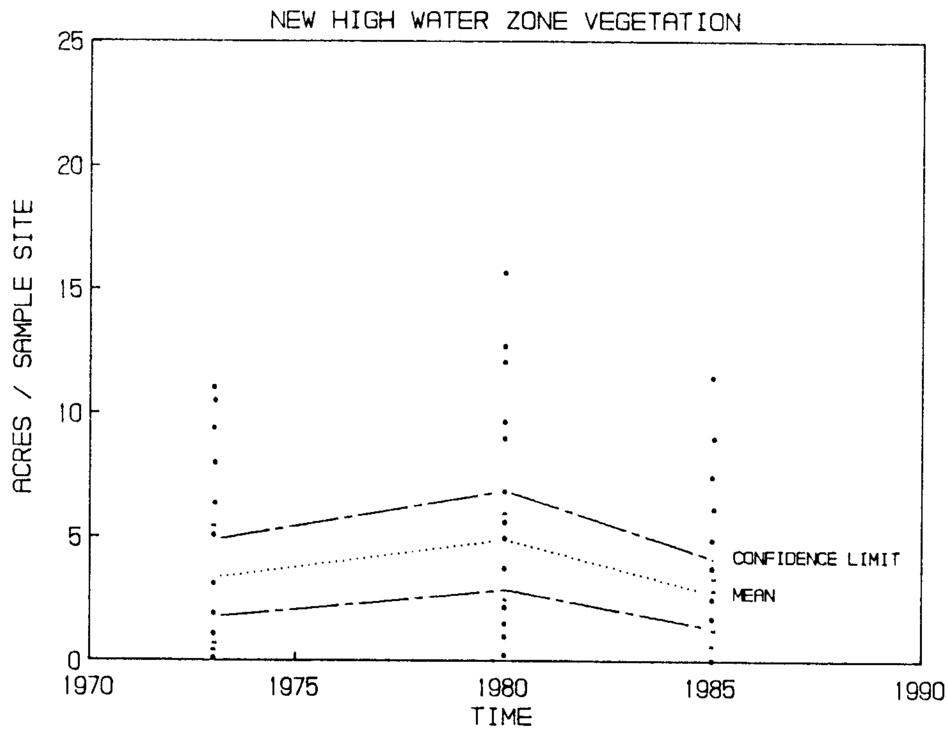

Figure 2b. Plant successional trends in the New High Water Zone.

The rasterized data were completed after applying the densities. We then extracted subset data by using the river mile overlay and reported it accordingly for the three complete dates: 1973, 1980, and 1985. The 1965 subset was handled by applying a substrata to extract only that portion of vegetation that was interpreted on the 1965 imagery. Because funding was not available to do the entire reach, very small reaches were analyzed on the 1965 imagery (approximately 0.5 miles of river per subset). To summarize, each subset was used as a separate strata to extract associated data from the other three. By using this computer technique, we have compared a small area using four dates of photography spanning 20 years of changes (Figure 3).

RESULTS AND DISCUSSION

The vegetation trends have been quantified. However, the author believes that trends from this study cannot be applied to the Grand Canyon riparian community as a whole. It is a very dynamic system. Variables such as micro-climates, tributaries, and substrate play an

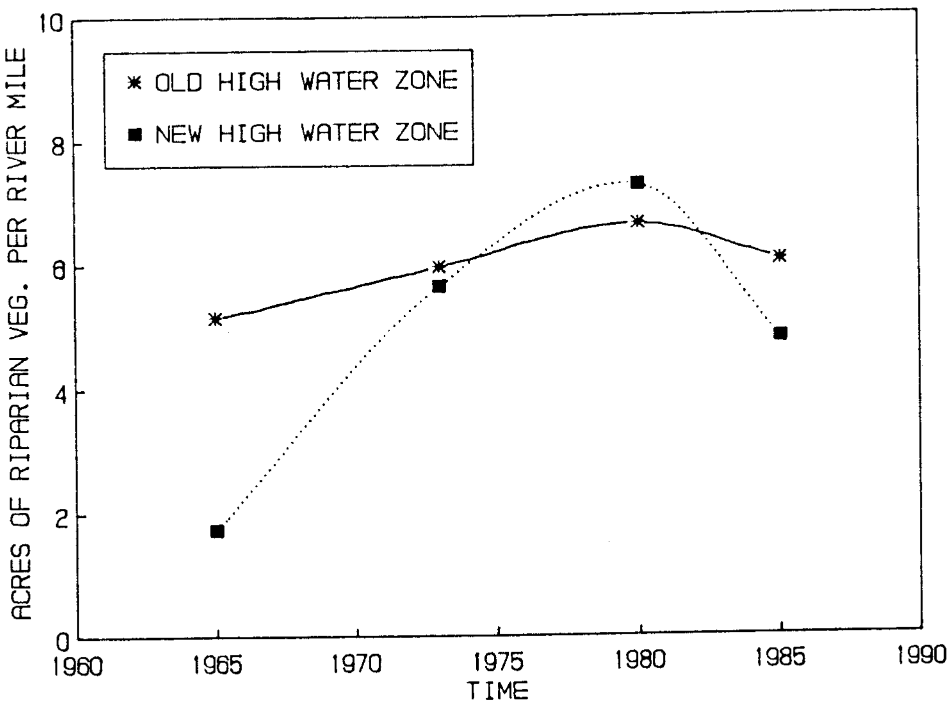

Figure 3. Post-dam average sub-plot vegetation at all sites.

important role with respect to natural succession of vegetation in the Grand Canyon. These variables and others need to be taken into account before we can determine trends within the entire system. The results are accurate as they apply to the selected sites and probably to areas with similar environmental factors.

With installation of Glen Canyon Dam in 1963, flooding conditions ceased and growth of the riverside NHWZ vegetation began. From 1965 to 1973, there was a large increase in this vegetation. This change was tabulated as +0.491 acre/river-mile/year. Around 1973, increase in cover slowed to approximately +0.264 acre/river-mile/year. This slowing of growth after ten years could be attributed to the NHWZ reaching or approaching a climax state. Our data indicate that since 1980 there has a been drastic decline in the NHWZ vegetation. This can be directly related to the flood of 1983. We used 1980 photographs for pre-flood conditions and 1985 data for post-flood conditions. We can say that, conservatively, the NHWZ vegetation lost -0.518 acre/river-mile/year since 1980. This rate would be higher if we took into account the fact that growth and establishment occurred between 1980 and 1983, and a major portion of the losses have occurred since 1983.

To summarize the NHWZ trend, the 1973 analysis indicated 76.647 acres of vegetation in the 19.2 miles surveyed. In the 1980 survey, we tabulated a significant increase of 35.501 acres, for a total of 112.148 acres of NHWZ vegetation in the riparian community. Applying the cover increase from this study, the vegetation in 1983 (the year of the flood) should have been approximately 127.206 acres, assuming that the system did not reach climax conditions. The flood was directly responsible for a significant loss of 49.684 acres of vegetation, bringing the NHWZ vegetation back to 77.522 acres, or 1973 conditions. The question is, will the NHWZ vegetation rejuvenate in ten years, and is there sufficient substrate to support this growth? The scenario just described is based on the assumption that no flooding occurred between 1965 and 1983; however, tributaries do frequently flash flood, impeding growth in those areas. Table 1 and Table 2 provide information on vegetation cover change in both NHWZ and OHWZ areas pertaining to specific study sites.

The OHWZ trend during the 1965-1973 period appears to be one of increasing cover, but at a rate five times slower than that of the NHWZ vegetation (+0.102 acre/river-mile/year). From 1973-1980, this increase

Table 1. Post-dam vegetation changes in the Grand Canyon, 1973-1985, using aerial photography (19.2 river miles surveyed).

River Mile Segment	7-Year Change 1973-1980		5-Year Change 1980-1985	
	NHWZ	OHWZ	NHWZ	OHWZ
44-45	+1.430	-0.359	-3.115	+ 1.035
45-46	+1.178	+0.164	-0.547	- 1.231
46-47	+1.047	+1.089	-0.612	- 2.607
47-47.5	+1.896	+1.707	-1.545	- 0.805
70-71	+5.156	-0.717	-6.652	+ 0.003
71-72	+3.250	-1.539	-5.247	- 1.710
72-73	+1.658	-3.649	-3.542	- 0.465
105.5-106	+0.252	+0.248	-0.214	+ 0.004
106-107	+0.118	+0.565	-0.178	- 0.250
107-108	+0.194	+0.164	-0.458	+ 0.219
108-108.4	+0.044	+0.050	-0.246	- 0.031
120-121	+0.666	+0.825	-0.711	- 0.299
121-122	+0.119	+0.040	-0.237	- 0.028
122-123	+1.831	+0.494	-1.999	- 0.180
166.1-167	+2.921	+2.883	-4.624	- 3.527
167-168	+2.502	+1.042	-3.126	- 1.724
168-168.7	+1.539	+3.147	-1.991	- 1.649
207-208	+3.942	+1.458	-4.111	- 5.137
208-209	+2.692	+3.194	-6.322	+ 0.255
209-209.2	+0.403	+0.048	-0.954	- 0.773
218.6-219	+0.187	-0.094	-0.152	+ 0.013
219-220	+1.440	+1.407	-1.875	- 1.560
220-220.6	+1.036	+0.456	-1.226	- 1.321
Total River Miles Surveyed (19.2)	+35.5010	+12.6230	-49.6840*	-21.768
Average Change/Year in 19.2 River Miles	+5.0716	+1.8033	-9.9360*	- 4.352
Average Change/ River Mile	+1.8490	+0.6574	-2.5877*	- 1.134
Average Change/ Year/River Mile	+0.2641	+0.0939	-0.5175*	- 0.227

* This decrease is mainly related to the flood of 1983.

Table 2. Post-dam vegetation changes in the Grand Canyon, 1965-1985, using aerial photography (4.05 river miles surveyed).

Area	1965-1973				1973-1980				1980-1985			
	Subplot 1		Subplot 2		Subplot 1		Subplot 2		Subplot 1		Subplot 2	
	NHWZ	OHWZ	NHWZ	OHWZ	NHWZ	OHWZ	NHWZ	OHWZ	NHWZ	OHWZ	NHWZ	OHWZ
Saddle	+1.323	-1.818	+3.390	+0.074	+1.658	+1.249	+0.834	-0.150	-0.423	-0.632	-0.738	+0.680
Cardenas	+3.649	+1.398	+3.216	+0.431	+0.478	-1.878	+0.780	-0.507	-0.570	+2.126	-2.846	-0.259
Bass Canyon	+0.083	+0.021	+0.274	+0.09	+0.069	-0.003	-0.003	+0.022	-0.146	+0.042	-0.118	-0.075
Forster	+0.012	+0.348	+0.063	+0.037	+0.435	+0.237	+0.307	+0.547	-0.464	+0.002	-0.318	-0.232
National	+0.815	-0.471	+0.62	+0.421	+0.837	+0.437	+0.231	+0.088	-0.974	-0.525	-0.678	-0.342
Granite Park	+1.334	-0.557	+0.689	+1.028	-0.231	+0.804	+0.170	+0.278	-0.066	-0.086	-0.497	-0.752
Granite Springs	+0.221	+2.101	+0.210	+0.215	+1.028	+1.615	+0.009	+0.001	-1.091	-2.162	-0.145	-0.177
TOTALS	+7.437	+1.022	+8.462	+2.296	+4.274	+2.461	+2.328	+0.279	-4.734	-1.235	-5.34	-1.157

Total River Miles Surveyed	1965-1973		1973-1980		1980-1985	
	NHWZ	OHWZ	NHWZ	OHWZ	NHWZ	OHWZ
4.05	15.892	3.318	6.602	2.74	-10.074*	-2.392
Average Change/ Year in 4.05 Miles	+1.9865	+0.4148	+0.9431	+0.3914	-2.0148*	-0.478
Average Change/ River Mile	+3.924	+0.8193	+1.6301	+0.6765	-2.4874*	-0.5906
Average Change/ Year/ River Mile	+0.4905	+0.1024	+0.2329	+0.0966	-0.4975*	-0.118

* This decrease is mainly related to the flood of 1983.

in cover was slightly lower at +0.094 acre/river-mile/year. The data from the period 1980-1985 revealed a significant decrease in cover of -0.227 acre/river-mile/year. It should be noted that 17 of the 23 study plots showed a decrease in vegetation cover. To summarize the OHWZ trend, the 1973 analysis indicated 112.35 acres of OHWZ vegetation in the 19.2 miles of river surveyed. In the 1980 survey, we tabulated an insignificant increase of 12.625 acres, yielding 124.976 acres of OHWZ vegetation in the riparian community. The 1985 data showed 103.21 acres of vegetation, or a significant loss of 21.766 acres in the OHWZ. Table 3 presents t-test results indicating where significant changes have occurred.

During the course of this study, I visited the Grand Canyon three times. Personal observations indicate that a dieback of the OHWZ vegetation is occurring. Any increase in growth that could have resulted from flooding in 1983 is not yet detectable on the aerial photographs. Another inventory with 1990 aerial photographs would help verify these observations.

CONCLUSIONS

The NHWZ showed a significant increase in vegetated cover from 1965 to 1980 and a significant decrease in cover after the flood in 1983. The OHWZ showed no significant change in cover from 1965 to 1980 and a significant decrease in cover from 1980 to 1985. If the flood in 1983 increased growth in the OHWZ by increasing water availability, the change was not yet detectable on the 1985 photographs. Future surveys will be needed to determine long-term effects of flooding in the NHWZ and OHWZ.

RECOMMENDATIONS

Recommendations for future monitoring of vegetation trends are: (1) continue work using these methods in 5- to 7-year increments, (2) use map bases if they become available, and (3) address the trends in the entire Grand Canyon. A random sample of new study sites should be developed to arrive at an extrapolative data set. We could then identify vegetation trends in the entire Grand Canyon riparian system.

Table 3. Results of paired t-Test.

NHWZ			OHWZ		
1965-73	1973-80	1980-85	1965-73	1973-80	1980-85
n = 13	n = 22	n = 22	n = 13	n = 22	n = 22
t = 3.25*	t = 5.46*	t = 5.05*	t = 0.96	t = 1.77	t = 3.25*

* Indicates significant changes between the means at the 95% probability level (P = .05).

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EFFECTS OF POST-DAM FLOODING ON RIPARIAN SUBSTRATE, VEGETATION, AND INVERTEBRATE POPULATIONS IN THE COLORADO RIVER CORRIDOR IN GRAND CANYON

Recent post-dam flooding affected physical and chemical substrate characteristics and resulted in significant plant mortality in the riparian corridor of the Colorado River in Grand Canyon. These impacts, as well as the effects of flooding on invertebrate population dynamics and the trophic structure of the riparian ecosystem, are discussed in relation to an assessment of the operating criteria of Glen Canyon Dam.

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INTRODUCTION

The effects of regulated discharge on terrestrial riparian soils, vegetation, and animal life are significant and complex, yet have received little attention from pedologists, ecologists, and habitat managers. The lack of research in this field is unfortunate given the general wildlife and recreational value of the riparian ecosystems which develop downstream from dams (Johnson and Jones 1977; Johnson et al. 1985). In this study, we documented changes in physical and chemical substrate characteristics, riparian plant populations, and riparian invertebrate populations that took place as a consequence of spillover flooding in 1983, 1984, and 1985 in the post-dam Colorado River riparian corridor in Grand Canyon, Arizona. With the completion of Glen Canyon Dam in 1963, the flow regime of the Colorado River was altered from extreme variability to a more stable pattern (Howard and Dolan 1981), and the riparian zone became available to perennial plants (Turner and Karpiscak 1980). The most common colonizing species was exotic *Tamarix chinensis*. From about 1970, *Salix exigua*, *Tessaria sericea*, *Baccharis* spp., *Prosopis glandulosa*, *Acacia greggii*, and other native species also began to colonize this system (Martin, unpublished 1971). Invertebrate and vertebrate population density and diversity also increased in the post-dam riparian zone (Carothers and Aitchison 1976; Carothers et al. 1979). Flooding was rare as the reservoir filled, and regulated flows seldom exceeded 30,000 cubic feet per second (cfs). When Lake Powell reached maximum capacity in 1980, a 49,500 cfs flood passed through the river corridor. In the spring of 1983, above-normal winter snowfalls resulted in a record release of 92,600 cfs from Glen Canyon Dam. In 1984, and again in 1985, summertime flows were maintained at or above 40,000 cfs for prolonged periods, and flooding continued to affect edaphic processes, riparian vegetation, and terrestrial animal life along the Colorado River in Grand Canyon.

This study was designed to assess the effects of recent flooding on: (1) chemical and physical characteristics of terrestrial riparian substrates as these parameters relate to growing conditions for riparian plants, (2) the riparian plant community itself, and (3) riparian invertebrate populations associated with that vegetation. Thus, whether from the standpoint of soils or of herbivores, we were primarily concerned with the effects of flooding on the producer trophic level in this ecosystem: riparian plant survivorship, establishment, growth, and population dynamics.

METHODS

Flood zones were defined as follows: Zone A extended from the 20,000 cfs discharge stage to 40,000 cfs and was the zone of greatest flooding impact, Zone B lay between 40,000 cfs and 60,000 cfs and sustained less prolonged inundation in 1983, Zone C lay between 60,000 cfs and 92,000 cfs at the top of the 1983 flood zone, and Zone D lay above the 92,000 cfs stage--above the zone of impact from the 1983 flooding event. The approximate discharge stage of a sample site was determined by its location in relation to known high water lines, including those marking the top of the 1983 flood zone. Relatively constant discharge during the first half of 1984 left a distinct "bathtub ring" along the riverbank at approximately the 42,000 cfs level, which served as a useful reference during our sampling. Field research was conducted from three white-water rafting trips and several land-based expeditions in 1984 and 1985.

SUBSTRATE ANALYSES. We examined riparian substrates to determine the effects on substrate characteristics of discharge stage; river reach type (eddy, straight, riffle, or rapid); distance from Glen Canyon Dam; and vegetation cover. Scala (unpublished 1984) sampled Grand Canyon riparian substrates in 1981. In the summer and fall of 1984, we resampled 20 of his sites that best represented characteristic flood zones, terraces, cover types, and substrates. Sites with minimal disturbance from tributaries and human (recreational) impacts were chosen. We collected our samples using the existing substrate surface as our baseline. At each site, a 1.5 m hole was excavated and 500 g samples were extracted at depths of 5, 35, 50, 75, 100 and 150 cm (where possible), relative to the surface. Samples were extracted with a plastic scoop to prevent contamination and transported to the laboratory where they were air-dried at 20 degrees C prior to analysis. For 17 of the 20 sites, we obtained Scala's (op. cit.) original 1981 35 cm-depth samples, which we compared with our surface-relative 1984 samples. In the laboratory, we performed the following standard soil analyses (Black 1967; Folk 1980; Page et al. 1982):

(1) pH was determined using colorimetric and electronic techniques.

(2) Base cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) were extracted using a 0.05 NHCl + 0.025 NH_2SO_4 acid solution in acid-washed glassware, then filtered twice. We determined base cation concentrations under standard conditions using a Perkin-Elmer 560 Atomic Absorption Spectrophotometer (Perkin-Elmer 1982). To ensure precision, we verified the acid equivalence of the extraction solution against a known concentration of NaOH. The acid equivalence proved to be 0.077 N acid, extremely close to the 0.075 N required by the extraction protocol.

(3) We analyzed burnable organic content plus carbonates for samples at 35 cm depth for which matching samples from the 1981 survey were available. Samples were dried at 100 degrees C to constant weight, then weighed. They were then ashed at 500 degrees C to constant weight, and reweighed.

(4) Substrate texture (percent sand, silt + clay, and clay) was determined through mechanical sieving and with the Bouyoucos (1927) hydrometer technique.

We analyzed substrate data using SPSS (Nie et al. 1975) and Minitab (Ryan et al. 1976) statistical packages with analysis of variance, linear regression, and student's t-test statistics.

RIPARIAN VEGETATION. Inspection of the river corridor in the fall of 1983 revealed three sources of flood-induced plant mortality: (1) direct removal of plants by scouring, (2) drowning under prolonged flows, and (3) burial under redeposited fluvial sediments. To assess levels of plant removal, data were collected from several sources: transect and quadrat data, marked individual plants, and ground photographs of the riparian corridor from 1980 through 1984. Information gathered from all sources included plant species, height, and condition. Independent stems and distinct clumps were considered as single individuals. Data on plants larger than the seedling sizes from the Zones A and B were pooled for analysis of removal.

Mortality due to drowning of all perennial riparian species was derived from several data sets. Mortality was measured on 47 quadrats in 1984. Twelve of these sites were censused again in 1985. Quadrat sites were selected in the four reach types throughout the river corridor. Each quadrat was 30 m in length and extended to the top of Zone C. The number and heights of live and dead plants (including seedlings) of each species were determined for each zone of each quadrat, and quadrat width was measured. All plants on more than 3.68 ha of riparian habitat were examined in 1984 in quadrat analyses. Other drowning mortality data were derived from transects used to assess removal, and from several additional 10 m X 30 m study plots (Stevens, unpublished 1985).

Mortality due to burial under redeposited fluvial sediments was difficult to distinguish from drowning; however, field observations provided evidence of the importance of this source of mortality. Removal and drowning mortality levels were averaged by type to obtain an estimate of mortality by species. Data were analyzed using X^2 statistics with the Yates correction for continuity (Brower and Zar 1977), as well as multiple linear regression and analyses of variance (Snedecor and Cochran 1980).

The effects of distance from Glen Canyon Dam, reach type (eddy, straight, riffle, or rapid), substrate type (silt, sand, cobble, mixed, or bedrock), and stem height on plant mortality due to drowning were assessed using quadrat data. Analyses of variance of mortality with these location and position factors were performed using BMDP statistical programs (Dixon 1983). To assess changes in vegetation diversity and community structure in this system, we calculated standard indices of diversity and evenness (Brower and Zar 1977) using 1984 data from six quadrats in each of four reach types for the common riparian perennial species (n=24 quadrats).

INVERTEBRATE COMMUNITY DYNAMICS. To address the issue of how phytophagous insect and chironomid midge populations responded to flooding, we sampled six 10 m X 30 m *Tamarix* and *S. exigua* sites in 1984 and 1985. These study sites were established in pure, even stands of vegetation undisturbed by river recreationists. *Tamarix* sites included River Mile (RM) 0.1R, T1 (RM 43.5L), RM 48.4R, RM 143.2R, T3 (RM 169.5R), and T4 (RM 205.0L). *Salix* sites included stands at RM 1.2R, RM 43.1R, RM 50.2R, RM 64.8R, RM 122.2R, and RM 133.5R. At each site, fifty 2 m sweeps were made in vegetation with a cloth insect net in full sunlight. Invertebrates were killed with ethyl acetate, and samples were returned to the laboratory for analysis. Specimens were identified to species, counted, and classified by guild as herbivores, predators, parasitoids, or incidentally-occurring species. Specimens were sent to the U.S. Department of Agriculture Insect Identification and Beneficial Insect Introduction Laboratory in Beltsville, Maryland for identification.

Invertebrate data were compared and contrasted using t-tests and analysis of variance. To compare patterns in phytophagous herbivore community structure and similarity before and after flooding on *S. exigua* and *Tamarix*, we calculated evenness (Pielou's J, Brower and Zar 1977) and an index of community similarity (Stander 1970). Observations on the trophic dynamics between fluvial and riparian components of this ecosystem were made in the field, and a general description of trophic interactions was developed from these observations.

RESULTS

EFFECTS OF FLOODING ON RIPARIAN SUBSTRATES. The survey of riparian substrates provided insights into pedogenesis and flood-induced edaphic change in this system. Pre-dam sediments consist of interbedded laminae of texturally uniform, hydrophobic silt loam, loam, sandy loam, loamy sand or sand. Sampling sites that lay within the inundation zone of the 1983 flood were altered by moderate to extreme devegetation, scouring of the substrate, and redeposition of fluvial sediments. In 1984, the Zone A and B beach substrates were characterized by young, unweathered xerifluventic substrates with moderately high pH, low organic content, sand/loam textures, and base cation ratios of:

$$Ca^{2+} >> Mg^{2+} >> Na^{+} > K^{+}$$

Samples collected in 1984 revealed significant changes in physical and chemical substrate characteristics, relative to substrate surface level, as compared to samples collected before flooding in 1981:

(a) Substrate pH differences between various vegetation cover types in the inundated zone were more homogeneous.

(b) Monovalent and, to a lesser extent, divalent base cation concentrations (except Mg2+) declined significantly in the inundated zone between years. Cation concentration differences between the inundated and non-inundated zones generally became more pronounced following flooding.

(c) The percent burnable organic matter plus carbonates declined significantly in the inundated zone as a consequence of flooding.

(d) The percent sand in inundated zone beaches increased, and the percent silt + clay decreased significantly as a result of flooding.

Among the inundated sites, substrate quality beneath exotic _Tamarix_ stands was consistently better than that associated with native _Salix exigua_ stands or open beach sites. Reasons for this include the following: _Tamarix_ stands typically occupy erosion-resistant pre-dam silt beds, and _Tamarix_, a deeply rooted species, protected the substrate from flood-induced scouring better than did _Salix_.

Correlation of substrate characteristics with distance from Glen Canyon Dam was significant and positive for $Ca2^{+}$ concentration, percent burnable organics plus carbonates, and percent silt + clay. These relationships may be attributed to increased scouring near the dam with redeposition in the lower Grand Canyon and/or the influence of tributaries in this system. Analyses of base cation distribution with respect to depth in the profile showed that the "bulges" in concentrations found in pre-dam sediments were smaller and less conspicuous in the profiles of post-1983 inundated sites for all cation species.

Thus, the new beaches that formed as a result of flooding in 1983 exhibit significantly different chemical and physical properties from their predecessors. At the present time, riparian substrates in the inundated riparian corridor of the Colorado River in Grand Canyon are typified by pH values of approximately 8.0; low concentrations of monovalent Na+ (40.1 μg/g) and K^{+} (25.9 μg/g) and relatively high concentrations of divalent Ca^{2+} (1,314 µg/g) and Mg^{2+} (208.0 µg/g); extremely low organic content (<0.37 percent); and a sand texture (89 percent sand, approximately 9.5 percent silt, and less than 1 percent clay). Flooding/leaching in 1983 and 1984 significantly reduced base cation concentrations (except Mg^{2+}), percent organic content, and percent silt + clay (except where the substrate was protected by dense stands of Tamarix), as compared to 1981 data and relative to the surface level. The 1984 pH remained relatively unchanged, possibly as a consequence of the buffering effects afforded by elevated soil carbonate concentrations in this system.

These changes in physical and chemical substrate characteristics represent a significant deterioration in environmental conditions for surviving and future riparian plant life in the inundation zone. In particular, the increase in particle size of beach sediments in this system may lead to increased erosion rates, rapid leaching of nutrients, and more rapid desiccation of the substrate, conditions highly unfavorable to germinating plants. Pedogenesis of riparian substrates is a slow process, one facilitated by the growth of vegetation and negatively affected by flooding and other environmental disturbances. Maintenance or improvement of riparian substrate quality will require concerned, consistent management in this system.

EFFECTS OF FLOODING ON RIPARIAN VEGETATION. Record post-dam flooding in 1983 in the Colorado River corridor downstream from Glen Canyon Dam reduced the total number of individual riparian plants in Zones A and B by more than 50 percent (Table 1). Sources of mortality included removal by scouring, drowning, and burial under redeposited fluvial sediments. Various species of riparian plants responded differently to this disturbance event, depending on species' architecture, inundation tolerance, and burial tolerance.

(a) Tree-forming species with deep tap roots (e.g., Salix gooddingii, Prosopis, Acacia, and Tamarix) were differentially resistant to removal by scouring, as compared to clonal species (e.g., Salix exigua and Tessaria sericea) or other shallow-rooted species (Baccharis, Aplopappus, Brickellia, etc.).

Table 1. Mean percent removal, percent of remaining plants drowned, estimated total percent mortality, and seedling density/m^2 of common perennial plant species in the Colorado River Riparian corridor in Grand Canyon, 1984. Data pooled for zones A and B in straight and eddy reaches.

Species	Mean Percent Removal	N	Mean Percent Drowned	N	Estimated Total Percent Mortality	Mean Seedling Density/m^2
Deep Tap Roots						
Tamarix chinensis	19.32 **	4452	27.99 **	4584	41.90 **	0.491
Prosopis glandulosa	0.50 ns	108	44.79 **	303	45.06 **	0.001
Acacia greggii	9.09 ns	11	20.00 ns	39	27.27 ns	0.003
Salix gooddingii	0.00 ns	18	5.56 ns	18	5.56 ns	0.000
Clonal, Shallow Roots						
Salix exigua (ramet)	72.42 **	12828	11.99 **	4922	75.72 **	0.002 s
Salix exigua (genet)	16.18 ns	68	0.00 ns	68	16.18 ns	---
Tessaria sericea (ramet)	90.60 **	271	44.02 **	4073	94.74 **	0.083 s
Tessaria sericea (genet)	9.13 ns	32	0.00 ns	32	9.13 ns	---
Aster spinosus (genet)	---	---	19.02 **	413	19.02 **	0.017
Phragmites australis (genet)	42.31 *	26	0.00 ns	26	42.31 **	0.000
Typha latifolia (genet)	83.33 **	12	0.00 ns	12	83.33 **	0.000
Scirpus sp. (genet)	100.00 ns	2	0.00 ns	2	100.00 ns	0.000
Shallow Roots						
Baccharis salicifolia + *emoryi*	74.56 **	510	63.98 **	731	90.84 **	0.008
Baccharis sarothroides	20.72 **	1004	70.28 **	1216	76.44 **	0.004
Baccharis sergiloides	---	---	79.34 **	30	79.34 **	0.000
Brickellia longifolia	---	---	62.04 **	43	62.04 **	0.015
Aplopappus acradenius	---	---	83.23 **	113	83.23 **	0.005
Gutierrezia spp.	---	---	35.39 **	416	35.39 **	0.006
Encelia farinosa	---	---	63.64 **	55	63.64 **	0.001
Total Mean	23.82 **	6243	38.95 **	8101	53.49 ** (14344)	0.636

ns $p > 0.05$; * $p < 0.05$; ** $p < 0.01$; s = clonal sprouts, not seedlings

(b) Drowning and thrashing accounted for nearly 40 percent of the observed mortality. Salix, Acacia, Tamarix, and Tessaria were relatively resistant to drowning, while Prosopis, Baccharis, Brickellia, Aplopappus, and xeric-adapted species were poorly adapted to inundation stress.

(c) Species tolerant of burial included Tamarix and clonal Equisetum, Phragmites, Salix, Alhagi, Aster, and Tessaria, while those intolerant of burial included species which grew as clumps (Prosopis, Acacia, Baccharis, Brickellia, and xeric-adapted species).

Quadrat data show that plant mortality was strongly correlated with proximity to the river (and consequently discharge stage), with more than 49 percent mortality in Zone A, 26 percent mortality in Zone B, and nearly 18 percent mortality in Zone C. Plant mortality varied according to substrate type. Mortality was highest on cobble substrates, moderate on sand and mixed sand-cobble substrates, and lowest on bedrock. Mortality was intercorrelated with current velocity and substrate type. Both Salix and Tamarix were capable of rapid regrowth, but Salix grew faster than Tamarix in some settings. Post-flooding clonal reproduction in Salix exigua and Tessaria was vigorous, and these species rapidly invaded new sediment deposits in several reaches. Sexually-reproducing Tamarix and other species have been slower to recolonize habitat lost through flooding disturbance. Community diversity and structure (evenness) declined slightly but significantly in this system because of a reduction in Baccharis spp. and other species densities; however, no plant species were lost from the river corridor because of flooding. Flooding exposed the substrate beneath the stands of Tamarix and S. exigua to higher levels of insolation. Flooding in 1983 subsequently resulted in widespread germination of several riparian plant species, particularly Tamarix and, to a lesser extent, Baccharis and Brickellia. Seedlings of common clonal species, such as Salix exigua and Tessaria, were not found. Carefully controlled flooding and discharge might be used to shift the dominance of Tamarix in favor of native plant species in this system.

EFFECTS OF FLOODING ON INVERTEBRATE POPULATIONS. Extensive flood-induced loss of riparian vegetation and substrate in this system substantially reduced the total biomass of phytophagous, terrestrial, and fossorial riparian invertebrate life in 1983.

Outbreaks of invertebrate herbivores on Tamarix and, to a lesser extent, Salix exigua, appeared to be correlated with moderate levels of flooding, adequate summer precipitation, and parasitoid populations in this system. Normal (pre-1983) and high (e.g., 1983) discharges and low summer precipitation (e.g., 1985) resulted in low densities of invertebrate herbivores. Flooding temporarily decreased invertebrate herbivore species richness on Salix exigua, but not on Tamarix in this system, and phytophagous invertebrate populations recovered quickly. As compared to 1982, invertebrate herbivore community similarity declined in 1983 and 1984 on Salix exigua but remained relatively constant on Tamarix. In 1985 levels of community similarity were comparable to 1982 levels. Phytophagous invertebrate community similarity declined with distance downstream from Glen Canyon Dam for Tamarix but not for Salix exigua.

Adult chironomid midges comprise a significant proportion of the food resources available to predacious insects, amphibians, reptiles, and birds in this system. Chironomids prefer to alight on Salix rather than on Tamarix, and adult chironomid populations were lowest during years of high flows and large fluctuations (1980 and 1983). Changes in the population dynamics of several insect taxa were observed or inferred following post-1982 alterations in the discharge regime in this system. Orthopteran (e.g., Tridactylidae), coleopteran (e.g., Hydrophilis), and pestiferous dipteran (e.g., Ceratopogonidae and Tabanidae) populations increased, while hymenopteran (especially ant and sphecid wasp) populations declined. Trophic interactions between the riverine and terrestrial components of this ecosystem are complex and closely interrelated. Management of terrestrial resources in the Colorado River corridor in Grand Canyon will require a detailed appreciation of the major inter-relationships between these components.

DISCUSSION

Riparian lands have repeatedly been shown to be the most valuable and most abused habitats in the Southwest (Johnson and Carothers 1982; Johnson and Jones 1977; Johnson et al. 1985). The construction of Glen Canyon Dam accidentally created a riparian habitat of considerable worth to wildlife and recreation (Carothers and Aitchison 1976; Turner and Karpiscak 1980; Stevens, unpublished 1985), and the responsibility for the well-being of this riparian ecosystem rests squarely on the shoulders of the Bureau of Reclamation and the National Park Service.

Catastrophic flooding in 1983 and prolonged above-normal discharges in 1984 and 1985 have had at least three direct effects on the terrestrial riparian ecosystem in the Grand Canyon. First, flooding was a leaching event, resulting in marked decreases in substrate base cation concentrations (particularly monovalent cations), reduced organic matter, and reduced proportions of fine particle clays and silts in inundated substrates relative to the substrate surface level. Minor changes in substrate pH accompanied this event. These substrate changes may promote an increased rate of erosion of beach sands and represent a reduction in the nutritional value and water-holding capacity of beach sands, thereby reducing the quality of the habitat for seedling and adult riparian plants.

Second, flooding removed or drowned 50 percent of the riparian plants below the estimated 60,000 cfs stage, the zone in which post-dam vegetation was formerly most profuse (Stevens and Waring 1985). Total mortality was highest near the river and on sand and cobble substrates, and was strongly differential between species, with _Tamarix_, _Salix_ spp., _Acacia_, _Phragmites_, _Aster spinosus_, and _Tessaria_ faring better than _Prosopis_, _Typha_, _Baccharis_ spp. and _Brickellia_. Apparently, no plant species were lost from the river corridor through flooding; however, diversity and evenness of distribution of species declined slightly because of differential mortality. Flooding is believed to promote germination in the river corridor (Hayden, unpublished 1976), and germination continued in 1984 and 1985.

Third, flooding promoted changes in insect community dynamics on many levels in this system. Populations of phytophagous invertebrates on _Tamarix_ and _Salix_ were directly reduced by flooding. Unlike _S. exigua_, _Tamarix_ occupies non-inundated Zone D in this system, and populations of phytophagous insects on _Tamarix_--notably that of _Opsius stactogalus_ (Homoptera: Cicadellidae)--reinvaded inundated stands and reached outbreak proportions in 1984. Flooding reduced populations of fossorial and ground-dwelling invertebrates, including harvester ants, Apache cicadas, and other important taxa.

RECOMMENDATIONS

Recognizing the value of the riparian corridor for recreation and wildlife, and the need for appropriate, intentional management, how can the operation of Glen Canyon Dam prolong or facilitate the well-being of this system?

A baseloaded flow scenario is preferred for the riparian ecosystem in Grand Canyon. Steady flows would (1) minimize leaching and loss of base cations, nutrients, and fine particle riparian substrates; (2) minimize removal and drowning of riparian vegetation; (3) promote survival of established seedlings; and (4) encourage population stability of native invertebrate life.

Fluctuating flows with maximized power releases would prevent successful reestablishment and survival of native riparian plant species in the flood zone where that vegetation could be most prolific. Continued leaching and loss of nutrients and fine particles would be promoted by such a flow regime, and would bring a continued decline in habitat quality for vegetation. Extreme daily fluctuations may promote rapid leaching from beach and bank substrates as much as several meters above the water line.

THE TIMING OF SPILLOVERS AND LOW DISCHARGES. The flow regime under which the dam operates directly controls the development of terrestrial riparian vegetation and riparian community processes in this system. Biotic development below the 60,000 cfs stage (Zones A and B) can be maximized by limiting flooding disturbance and permitting the process of vegetational succession to occur; however, germination and colonization of riparian plants is promoted by rare, low magnitude/short duration flooding. Because riparian shrub and tree seedlings require several years of growth to withstand flooding (Kozlowski 1984; Stevens and Waring 1985), a flow scenario with an established maximum discharge level--one that minimizes bank-cutting erosion--with rare, low magnitude/short duration floods is considered best. A rare, low magnitude/duration flooding event might be worthwhile to this system on the order of once every 10 to 20 years. Ongoing studies will help clarify this issue.

In the event of future spills in this system, the timing of spills could conceivably be used to facilitate establishment of native plant species. Native species generally produce seeds in the middle and late summer, whereas exotic Tamarix produces most of its seed load in May and June. While flooding exerts negative effects on invertebrate populations regardless of the season, flooding should be avoided during the peak reproductive season for vertebrates.

Low-water years have been shown by Stevens (unpublished 1985) to exert negative impacts on Salix exigua growth. The preferred alternative for low-flow years is higher releases during the hottest, driest months (late May through mid-July) to protect established plants from desiccation.

From a practical standpoint, multiple use discharge management in this system will be difficult to achieve; however, spillover releases are wasteful, are potentially damaging to Glen Canyon Dam, and wreak havoc on the riparian ecosystem. The biotic and recreational value of the Colorado River riparian corridor in Grand Canyon justify its management as a resource worthy of preservation. Protection and improvement of this riparian system can only be achieved through a carefully considered policy of discharge management. We hope that this report contributes to an improved understanding and management of this system.

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AERIAL PHOTOGRAPHY COMPARISON OF 1983 HIGH FLOW IMPACTS TO VEGETATION AT EIGHT COLORADO RIVER BEACHES

Impacts to riparian vegetative cover at eight study plots following June 3 to August 11, 1983, high water releases from Glen Canyon Dam are compared using very large scale (1:250) vegetation maps drawn from 1982 and 1984 aerial photographs.

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INTRODUCTION

Unprecedented high flows coursed through Grand Canyon for 70 days from June 3 to August 11, 1983. Water exited Glen Canyon Dam from generator turbines, two spillway tunnels, and hollow jet valves. Discharge ranged from 38,000 cubic feet per second (cfs) to over 90,000 cfs. A flood peak of 92,500 cfs passed the Grand Canyon gaging station above Bright Angel Creek at 0800 hours on June 29. Flows exceeding 40,000 cfs inundated riverine beaches to various degrees, with most beaches and concomitant vegetation submerged at the highest flow (Brian and Thomas 1984). Vegetation located below the 92,500 cfs inundation line was either removed, buried, damaged, killed in situ, or unharmed. Alluvial sediments were actively reworked on site, transported and redeposited downstream, or removed from the system to Lake Mead. Beach profiles were altered (Beus et al. 1984). This study assesses vegetative cover change nine months after the high flows by comparing vegetation maps from 1982 and 1984. Change in beach vegetation below and above the line marking the flood peak is also discussed.

METHODS

Terrestrial habitat change was quantified by comparing the change in vascular plant canopies from eight study plots (approximately 100 m by 50 m) using computer-fitted vegetation maps drawn from 1982 and 1984 black and white aerial photographs (Figure 1, Table 1). Photos were taken from a fixed-wing aircraft from an average height of 500 ft (150 m) above the site. Portions of the 9-1/2 inch negatives were enlarged by a factor of four to an average scale of 1:250. False-color infrared photographs were used to define shaded canopies. Pre-high flow photos (November 1982) and

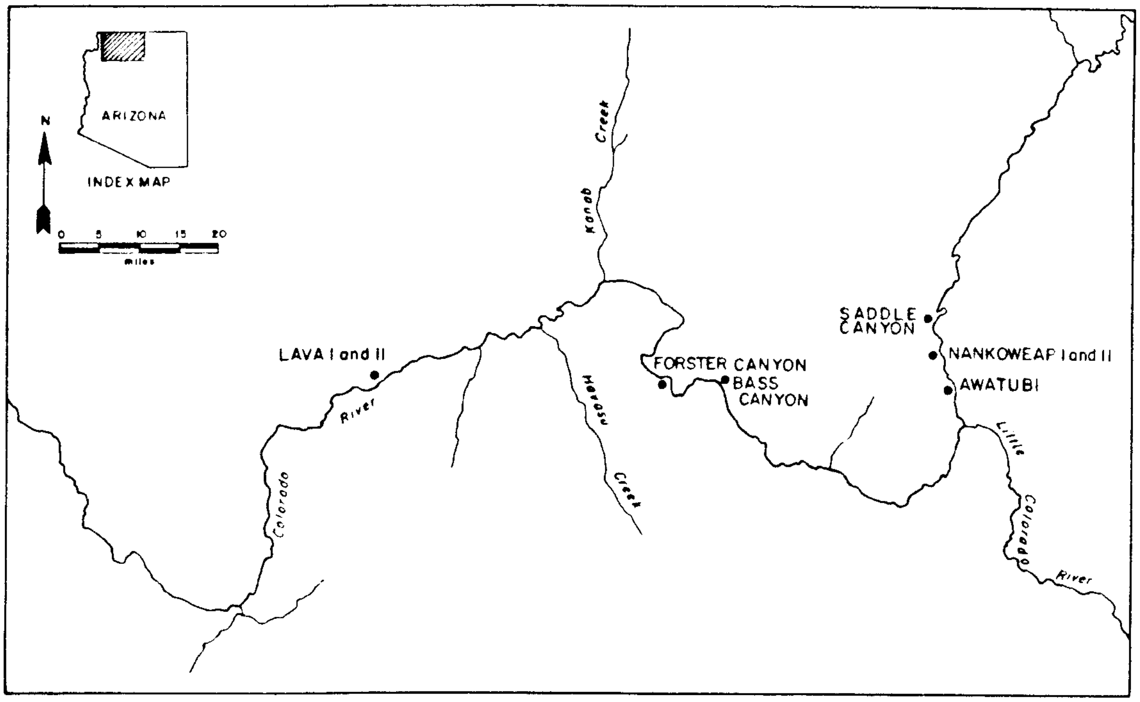

Figure 1. Map of the Colorado River through Grand Canyon National Park with location of the study sites.

post-high flow photos (May 1984) were taken between 1000 and 1400 hours with less than 10 percent cloud cover.

The 1982 vegetation maps had been prepared for a previous beach monitoring program (Johnson et al. 1983), and the 1984 vegetation maps were prepared by the author. In both cases, the plant canopies were first outlined on polyester drafting film or mylar, then field-checked and identified by a number for analysis. A total of 51 species were identified with 24 combinations of two or more species (indicating double or triple cover). All species are common inhabitants of southwestern riparian ecosystems and none are listed or proposed for federal protection. Annual plants which had germinated and grown since the date of photography were not included in the 1984 vegetation maps. The 1982 and 1984 aerial photos, vegetation maps, and computer images (Brian 1987) are not included in this report summary.

Table 1. Eight Colorado River study sites by location, River Mile below Lees Ferry and Glen Canyon Dam, and major study segment. River reaches are defined as: Reach I=Glen Canyon Dam to Lees Ferry, Reach 2=Lees Ferry to Little Colorado River, Reach 3=Little Colorado River to Phantom Ranch, Reach 4=Phantom Ranch to National Canyon, and Reach 5=National Canyon to Diamond Creek.

Study Site	Site Location	River Mile Below Lees Ferry	River Mile Below Glen Canyon Dam	Major Study Segment
Saddle	Saddle Canyon	47.2	62.2	Reach 2
Nankoweap I	Nankoweap (upstream site)	53.0	68.0	Reach 2
Nankoweap II	Nankoweap (downstream site)	53.0	68.0	Reach 2
Awatubi	Awatubi Canyon	58.2	73.2	Reach 2
Bass	Bass Camp	108.2	123.3	Reach 4
Forster	Forster Canyon	122.6	137.6	Reach 4
Lava I	6 Miles below Lava Falls	185.3	200.3	Reach 5
Lava II	6 Miles below Lava Falls	185.4	200.4	Reach 5

The 1982 and 1984 vegetation maps were digitized using an Altec Digitizer (with an accuracy of .001 cm) coupled to a Digital Equipment Corporation PDP 11-44 computer and checked for accuracy on a CalComp 925/748 Graphic Controller System and Plotter. A variety of Fortran programs manipulated the data files to calculate the area of each species or combination of species. Only the sum of the species area was calculated, not the area of individual plants. The resolution was set at a square pixel or picture element of 1/8 m^2 (12.4 cm^2) to allow a plant with a diameter of 24 cm to be identified. A histogram was produced listing the percent cover and frequency (sum of pixels) for all species, sites, and photo vintages.

Analysis of change from 1982 to 1984 over an entire study plot revealed the gross impact of the 1983 flood event. For example, a site with the majority of the plot situated above the 1983 flood line showed less impact than did a site in which the majority of the area was inundated and scoured by the floodwaters. Cover change from 1982 to 1984 was better viewed by assessing percent change below various water levels. Four water levels within the eight study plots were identified from photographic evidence and field inspection. The discharge at each level was verified using the Stream Synthesis and Reservoir Regulation streamflow routing model developed by the U.S. Army Corps of Engineers and calibrated for use in Grand Canyon by the Bureau of Reclamation, Durango Projects Office in 1980. The average flow divides each study plot into five zones:

Zone A :	Below 13,900 cfs
Zone B :	Below 43,000 cfs
Zone C :	Below 65,000 cfs
Zone D :	Below 92,500 cfs
Zone E :	Above 92,500 cfs

Each successive flow zone from Zone A to Zone D includes the area below it. For example, Zone C includes all area below the 65,000 cfs water line. Zone E includes all area above the flood peak. As topography, placement, and orientation of the study plots differ, the area occupied by each water zone varies. However, the greatest percentage of area (40 percent) is located below the 43,000 cfs water line (Zone B). To assess change within the five flow zones, water lines were masked over the vegetation maps, and percent cover and frequency were derived for all species, sites, and photo vintages.

Percent cover change from 1982 to 1984 was compared in three ways. First, total species cover was evaluated by site. Second, individual species cover was examined for each of the five documented water zones. And third, cover of "indicator" or representative, dominant species was evaluated for the three riparian communities: Old High Water Zone (OHWZ), Beach Zone, and New High Water Zone (NHWZ).

RESULTS

SPECIES COVER PER SITE. A comparison of percent differences (percent 1984 cover minus percent 1982 cover) for all species for all study plots (Figure 2)

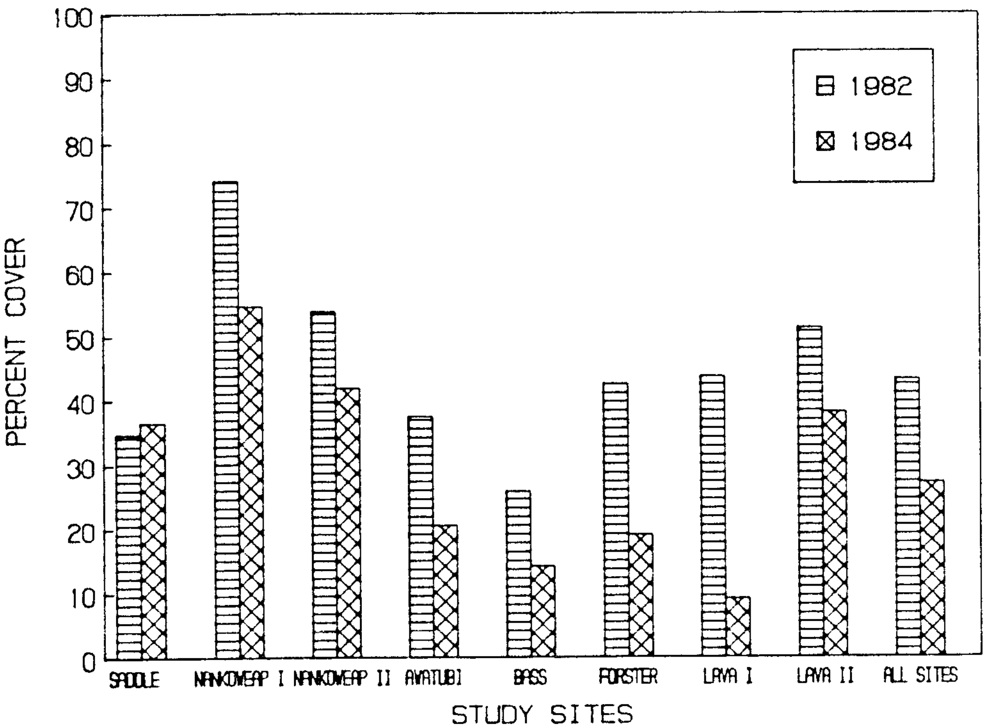

Figure 2. Percent cover of plants by study site and for all sites by year.

shows a 16 percent average decrease in plant cover with a resultant 16 percent increase in non-vegetated area. By ranking the study sites, the greatest decrease in plant cover is found in the Lava I site (34 percent). Only the Saddle site shows an increase in plant cover (almost 20 percent). A comparison of percent change (percent 1984 cover divided by percent 1982 cover) for all species for all study plots (Figure 3) shows a similar ranking from greatest to least change with an average 35 percent decrease in plant cover for all sites after the 1983 flood event. This is a more meaningful way to compare plant cover change because sites vary in size, shape, orientation, and height above the river channel. Percent cover change equalizes site to site differences. In assessing percent change for the 51 vascular plant species with single cover, 45 percent decreased cover, 25 percent were removed by the 1983 high flows, 18 percent increased cover, and 11 percent new to the 1984 plots increased cover. For the canopies of 26 species with combinations of cover, 73 percent were removed by the high flows, 15 percent new to the 1984 plots increased in cover, and 12 percent decreased in cover.

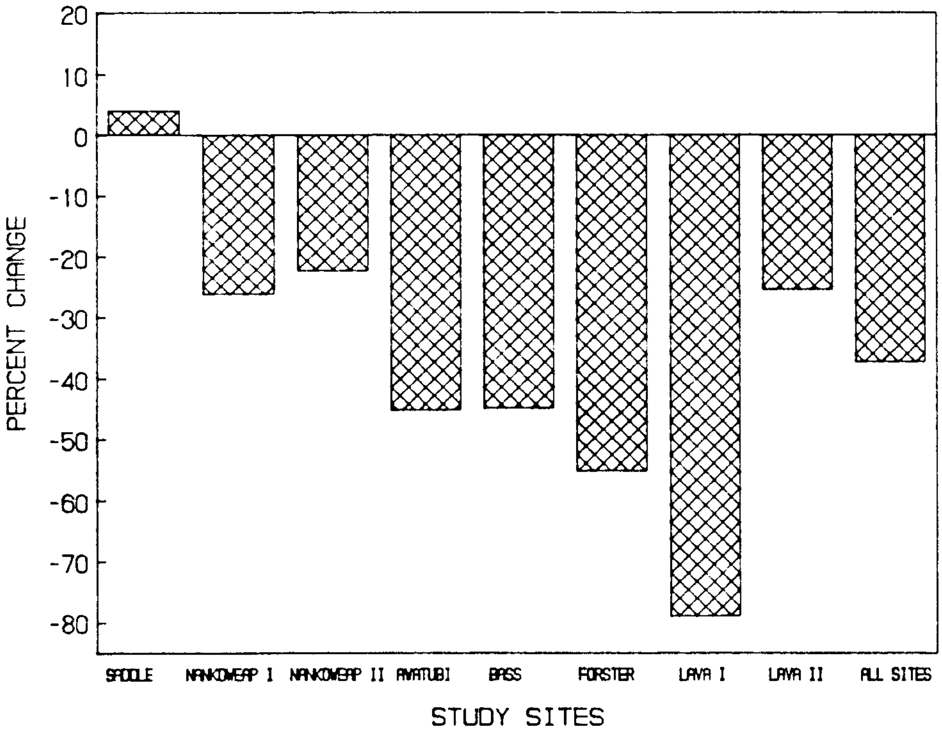

Figure 3. Percent change by study site and for all sites.

SPECIES COVER PER WATER ZONE. Species percent cover varied widely by water zone for each study plot. The fate of a particular species may be influenced by many factors, among them: proximity to Glen Canyon Dam, age of individual, protection afforded by nearby plants or physical structures, stem flexibility, root anchoring, woody versus herbaceous nature, amount of damage (by water flow, sand abrasion, foraging herbivores, boats, river runners, etc.), loss of substrate, and burial by redeposited sediments. Post-flood conditions may have affected plant growth in the study plots; however, it is assumed that change below the 92,500 cfs shoreline is due directly or indirectly to the flood event and not to the continuation of a vegetative successional trend. Factors contributing to change above the flood peak include: bank saturation transporting water and nutrients to plants of the OHWZ (which had been isolated from the river regime for 20 years), damage by river runners who camped by necessity in previously uncamped areas, continuation of vegetative succession, and/or seasonal differences.

By averaging percent cover change for all sites, cover decreased 87 percent below 43,000 cfs (for the six sites with area at this stage), 196 percent below 65,000 cfs, and 225 percent below 92,500 cfs. Below the flood crest, Forster showed the greatest decrease in percent cover (473 percent), followed by Awatubi (316 percent) and Bass (252 percent). Above the 92,500 cfs flood crest, average percent plant cover increased 108 percent. Four sites showed an increase in percent cover, with two sites, Forster and Awatubi gaining 625 percent and 375 percent, respectively. Three sites showed a decrease in percent plant cover above 92,500 cfs: Saddle (152 percent), Nankoweap I (91 percent), and Lava II (16.5 percent).

Data initially suggested that, generally, more damage or loss of plant cover occurred with distance downstream from Glen Canyon Dam. When percent cover change for all plots was averaged by major study segment (river reach), figures indicated increasing downstream loss: Reach 2 showed the least loss (22 percent), with greater loss shown by Reach 4 (50 percent), and greatest loss shown by Reach 5 (52 percent). However, when the specific plant species were assessed by water zone, the previous results were seen to be misleading. Greatest loss was found at sites which had a majority of the plot situated below the flood line and supported an assemblage of plants unable to withstand the scouring action of floodwaters (i.e., Tessaria sericea) (Turner and Karpiscak 1980), or were situated at the outside of a river bend (i.e., Forster). If percent cover change is averaged by study plots below the 92,500 cfs flood peak, greatest loss is shown by Reach 4 (363 percent), with about half as much change shown in both Reaches 5 (188 percent) and 2 (175 percent).

INDICATOR SPECIES COVER PER VEGETATION ZONE. Three post-dam riparian vegetative habitats have been identified in the Grand Canyon: Old High Water Zone (delineating the pre-dam ca. 120,000 cfs flood line), New High Water Zone (a dense jungle which rapidly proliferated along the post-dam river level), and Beach Zone (spanning the area between the new and old high water communities) (Carothers and Aitchison 1976). The pre-dam scouring floodwaters maintained a sharply defined limit below the old high water community, and today the three vegetative zones are generally distinct. Response to the 1983 flood event varied by vegetative communities and their associated dominant species both below and above the 92,500 cfs flood line.

Old High Water Zone: OHWZ water leguminous tree species increased 47 percent below the flood line and 57 percent above the flood line. Prosopis glandulosa (western honey mesquite) increased 68 percent below the flood line and decreased slightly (5 percent) above the flood line. Acacia greggii (catclaw acacia) increased 25 percent below the flood line and increased 119 percent above the flood line.

Beach Zone: Percent cover of four dominant, perennial bunch grasses (Aristida parishii, Oryzopsis hymenoides, Sporobolus spp., and Andropogon glomeratus) found at all study plots was averaged to exemplify change in the Beach Zone. The grasses were decreased by 42 percent below the flood line and increased by 56 percent above the flood line.

New High Water Zone: New riparian zone species decreased by 31 percent below the flood line and increased by 4 percent above the flood line. Tamarix chinensis (tamarisk, or salt cedar) exhibited little change as a result of the flood, losing little cover (0.5 percent) below the flood line and increasing slightly (11 percent) above the flood line. Salix exigua (coyote willow) decreased 42 percent below the flood line, and one plant was displaced by floodwaters above the 92,500 cfs line. Tessaria sericea (arrowweed) cover was halved (51 percent) below the flood line and was slightly reduced (3 percent) above the flood line.

DISCUSSION

Impact of the 1983 flood event to vegetation was determined more by interrelated factors within the immediate environment (i.e., site orientation, physical floodplain dynamics, and plant composition) than by distance downstream from Glen Canyon Dam. Study plots varied in placement, orientation, profile, degree of submergence by the floodwaters, and colonization by the heterogeneous assemblage of riparian species. However, three vegetation communities with various seral aspects were found at all study sites. Response was varied to inundation, submergence, and burial by redeposited sediments. Generally, native species (i.e., Salix exigua, Tessaria sericea, and the perennial bunch grasses) were reduced in cover, while the exotic Tamarix chinensis was little impacted below the flood peak. Vegetative succession was set back a decade or more, but recolonization will be rapid due to clonal ramification and a ready seed source from flood survivors. If high flows had swept down Grand Canyon at a different volume, duration, or periodicity, effects would have varied from those seen.

Extensive erosion and subsequent loss of plant habitat is often a major long-term impact of flow regimes or flood events. Without substrate there can be no plant colonization and associated fauna. However, deposition can occur as well. During the 1983 high flows, the post-dam aggraded Colorado riverbed may have contributed sediments to streamflow which were redeposited upon river terraces (Howard and Dolan 1981). The degree to which future floods degrade or aggrade Colorado River beach profiles will depend upon the extent of riverbed degradation by the 1983 flood, the amount of tributary sediment input during the years prior to the next flood event, and the amount of sediment future flows entrain and/or redeposit.

High water runoff years are part of the historic cycle of the Colorado River. Pre-dam, ten-year interval floods of 123,000 cfs were typical (Dolan et al. 1974). Since completion of Glen Canyon Dam in 1963, lack of extreme high flows may have had an adverse effect on the OHWZ to the extent that it has been hypothesized that the leguminous trees there have become senescent (Turner and Karpiscak 1980). However, it appears that the 1983 floodwaters benefited the dominant OHWZ trees as average percent cover above the 92,500 cfs flood line increased 57 percent from 1982 to 1984. To maintain the vigor of the Old High Water Zone, a relic of the pre-dam riverine ecosystem, it may be prudent to release high flows of 90,000 cfs during high water runoff years to surcharge the pre-dam river terraces.

CONCLUSIONS AND RECOMMENDATIONS

Maximum contemporary releases of 31,000-33,500 cfs from Glen Canyon Dam have negligible direct, injurious impact to the NHWZ. Some vegetation is inundated but established plants remain intact. Controlled minimum-maximum releases maintain a wetted perimeter of the river channel and create conditions favorable to establishment of new high water species as well as old high water species whose seeds are present along the post-dam shoreline. Recolonization of the Beach Zone and growth of the high water community will continue, albeit at a reduced pace. Extreme high water releases at 10- to 20-year intervals would preserve the old high water community by providing water and nutrients in the same fashion as historic old high flows. High flows would also thin growth of beach and riparian plants and redeposit entrained riverbed sediments upon beach terraces. Controlled minimum releases would allow New High Water Zone seedlings to become established below the post-dam shoreline. Short duration, minimum releases of 1,000-5,000 cfs during drought years would limit growth but community shifts would not be likely.

Time of year, stage, and duration of future flows are variables which will dictate the degree of impact to vegetation along the Colorado River corridor through Grand Canyon. The riparian communities are resilient and species are adapted to periodic flood disturbance and drought. Seedling and clonal species will recolonize beach sediments.

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THE EFFECTS OF RECENT FLOODING ON RIPARIAN PLANT ESTABLISHMENT IN GRAND CANYON

This is a summary of studies conducted on the reestablishment of riparian plants following the 1983 flood in Grand Canyon.

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INTRODUCTION

The 1983 flooding of the Colorado River in Grand Canyon caused many dramatic changes through the river corridor. From census studies, Stevens and Waring (1987) estimated that 50 percent of riparian or riverside plants were lost due to drowning or removal during the flood. Later, as floodwaters receded, beaches were colonized by large numbers of seedlings of many plant species. On some beaches, significant amounts of fine-grained sediments and organic and inorganic nutrients were lost by leaching and scouring during flooding, with mostly coarse-grained and relatively infertile sand being redeposited.

We regard these as the most pronounced and perhaps most influential consequences of the 1983 flood in the riparian plant community in Grand Canyon. One could hypothesize that the tight coupling of major mortality and germination events in these riparian species enables populations to persist in the midst of flooding. This possibility prompted us to ask the essential question of whether the 1986 populations are reaching pre-flood densities (implying replacement and perhaps equilibrium), or are they declining or perhaps even increasing in response to the flooding. We also examined the proximate factors, germination success, inundation (constant flooding), fluctuating flooding, desiccation, and substrate, as potential mechanisms behind patterns of plant establishment and mortality.

To address these issues we devised the following questions and predictions about plant establishment following the 1983 flood and have attempted to answer them in this study:

(1) Have densities of perennial riparian plants increased to or exceeded those of 1983? Put another way, is the plant community recovering from the 1983 flooding event?

(2) With respect to factors affecting plant establishment: (a) Do different durations and intensities of flooding such as fluctuating flows or constant inundations affect plants, especially younger plants, in a predictable manner? If they do (as we would predict), then concrete recommendations can be made about the flow regime which will allow as many seedlings as possible to become established in the future. (b) What is the role of changing substrate texture in the post-dam environment?

(3) When are seeds of riparian plants available in the environment to be recruited into populations, and does this vary among species?

While many perennial and annual plants occur along the river in Grand Canyon, we chose six of the most abundant species for investigation: the exotic tamarisk (Tamarix chinensis); the native clonal coyote willow (Salix exigua) and arrowweed (Tessaria sericea); and the composites seep-willow and desert broom (Baccharis spp.), including B. salicifolia, B. emoryi and B. sarothroides.

METHODS

ESTABLISHMENT OF SEEDLINGS IN GRAND CANYON. In 1984, we determined levels of colonization of seedlings at 49 quadrats throughout the Grand Canyon. From 1984 to 1986, in order to measure plant recruitment or establishment, we censused Tamarix chinensis, Salix exigua, Baccharis spp., and Tessaria sericea at 15 of the quadrats which were heavily colonized by seedlings in 1984 (following the 1983 flood). Sampling dates were June 21-July 7, 1984; June 1-17, 1985; and September 15-30, 1986. All individuals of each species were counted into one of four size classes: size class 1 (SC1) = 1-20 cm (seedlings), SC2 = > 20 cm - < 1 m, SC3 = > 1 m - < 2 m, SC4 = > 2 m. Changes in SC1 and SC2 densities between 1984 and 1986 then indicated whether plants established in 1984 have persisted.

MEASURING REPLACEMENT OF PLANTS LOST IN 1983 FLOODING. To determine if adult plants lost in the 1983 flood are being replaced, we compared the density of individuals dead in place due to drowning > SC2 in height in 1984 with the number of live individuals > SC2 in September, 1986, on the 15 quadrats censused. Because this measure of flood-related mortality substantially underestimated the density of dead individuals in 1984 by not accounting for mortality due to removal by scouring, we adjusted the density of dead individuals/m^2 in 1984 to include our estimates of removal rates for each species (Stevens and Waring 1987).

FACTORS AFFECTING SEEDLING ESTABLISHMENT. (1) Inundation, Fluctuating Flow and Desiccation Experiments. Percent survivorship of one-month-old and six-month-old seedlings of Tamarix, Salix, and Baccharis salicifolia under a variety of flooding and desiccation regimes was examined experimentally. Plants were reared in the Terrestrial Ecology Laboratory at Bilby Research Center at Northern Arizona University in Flagstaff, Arizona, from January 15 until June 15, 1986. For one-month-old plants, seeds of all species were germinated May 15, 1986. All potted plants were transported to Lees Ferry, Arizona, where experiments were conducted on June 20, 1986.

Seven treatments were run with ten replicates (pots) per treatment for six-month-old plants and nine replicates for one-month-old plants. Each pot contained 4-6 plants. The seven treatments are as follows:

(a) one month of inundation (I4 = Inundation for four weeks) in which pots were completely submerged in the Colorado River for one full month,
(b) two weeks full inundation (I2),
(c) one month fluctuating flows (F4 = Fluctuations for four weeks) in which the pots were completely submerged in the Colorado River for 12 hours during the day and removed for 12 hours at night every day for one month,
(d) two weeks fluctuating flows (F2),
(e) two weeks desiccation (D2) in which plants on shore were not watered for two weeks,
(f) one week desiccation (D1), and
(g) controls (grown on shore in partial shade, watered daily).

One-month treatments were conducted from June 20 to July 20 and two-week treatments ran from June 20 to July 4. At the end of this period, the percent of seedlings surviving per pot was calculated. We also studied effects of treatments on plant growth by measuring the growth of four plants/pot.

(2) Effects of Substrate on Seedling Germination. Tamarisk and coyote willow seeds were added to three-inch petri dishes containing silty soil (n = 6)

and coarse sand (n = 6) on June 27, 1986. The seedlings were allowed to germinate and at the end of ten days, percent germination/species/substrate type was determined.

(3) Effects of Substrate on Seedling Growth and Survivorship, Laboratory Experiments. Root and shoot growth rates in fine (pre-dam) versus coarse (post-dam) riparian sediments were compared for Tamarix chinensis, Salix exigua, and Baccharis salicifolia seedlings. Two- to four-day-old seedlings of these species were transferred to 3.5 cm X 30 cm glass tubes containing one or the other sediment type. After one month of growth, root length and shoot height were measured.

(4) Field Observations on Substrates Colonized by Tamarisk. Tamarisk densities were censused in sandy and cobble substrates. We censused three sites in the 40,000-60,000 cubic feet per second (cfs) zone in September 1986. Tamarisk seedling densities were measured in 30-50 randomly selected 1.0 m^2 plots in sand and in an equal number of randomly selected 1.0 m^2 plots in uniform cobble substrate.

We measured Tamarix survivorship and growth with proximity to the river and exposure to flooding. Young tamarisks were tagged with parakeet bird bands and their heights were measured in April and September 1986. Three stands of two-year-old plants were studied at River Mile [RM] 52R, RM 131R, and RM 171L; RM 52R was a protected, sandy site; RM 131R was a moderately protected cobble bar; and RM 171L was a sandy and exposed site.

TIMING OR PHENOLOGY OF PLANT REPRODUCTION IN GRAND CANYON. Reproductive phenology of tamarisk, coyote willow, seep-willow, desert broom, and arrowweed was measured during river and hiking expeditions (as well as on trips to the Lees Ferry area) between November 1985 and October 1986. We also examined herbarium specimens at the Museum of Northern Arizona in Flagstaff. We tagged 13 Tamarix chinensis at Lees Ferry and estimated the percentage of the canopy covered with flower heads at monthly intervals from April through October 1986.

RESULTS

ESTABLISHMENT OF SEEDLINGS IN GRAND CANYON. We found high levels of seedling colonization by the species of interest at 21 of 49 sites censused, meaning that extensive plant establishment occurred on 43 percent of the sites examined. At the undercolonized sites, densities of seedlings ranged from rare to nonexistent, so there was no reason to study them further in a colonization study. More cobble bar sites were extensively colonized than would be expected by chance alone, while fewer sand and talus sites were extensively colonized than would be predicted by chance alone ($X^2 = 5.0$, $p < .05$, $df = 1$). The cobble bar sites were colonized largely by sexually reproducing, seed dispersing tamarisk, and by Baccharis spp. In most cases, the sand substrate sites that were heavily colonized were invaded from the periphery by clonal coyote willow and/or arrowweed. Little colonization occurred on talus sites. Because of the extent of 1983 flood-induced adult plant mortality at most of the 49 quadrats, the plant system has not recovered to pre-flood densities. We believe that additional flooding since 1983 has contributed to this pattern.

At 15 of the sites on which substantial plant establishment has occurred, we found that seedling densities for three of four species did not vary significantly between 1984 and 1986. Densities of tamarisk in all size classes did increase significantly between 1984 and 1986. Densities of other larger plants were either no different from or, in the case of seep-willow, exceeded those of 1984. These patterns suggest that locally, large numbers of young recruits are entering the system on some beaches. This means that once established, plants are surviving in large numbers.

Clonal colonization by willow and arrowweed occurred mainly on quadrats with sandy substrates, while tamarisk and seep-willow seedlings were most common on cobble bars. This reflects a major shift in substrate-type colonized, particularly for tamarisk, older stands of which are mostly found on silt bars.

REPLACEMENT OF PLANTS LOST IN THE 1983 FLOOD. Our comparison of densities of live stems in 1986 to densities of dead stems (both adjusted and unadjusted for removal mortality) in 1984 revealed no significant differences between the groups for any species (Figure 1), implying that plant populations may be replacing themselves on some beaches. Paired t-test values were nonsignificant ($p > 0.05$) for the densities of dead 1984 (adjusted and unadjusted) versus live 1986 adult tamarisks ($df = 14$ quadrats), seep-willow and desert broom ($df = 13$), coyote willow ($df = 5$), and arrowweed ($df = 4$).

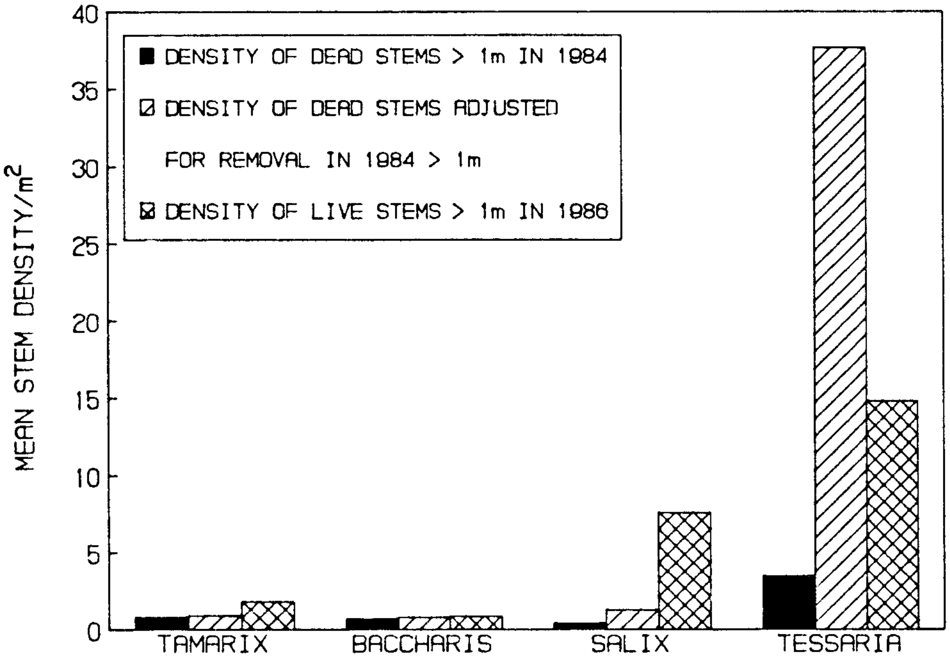

Figure 1. A comparison of the density of dead stems (unadjusted and adjusted for removal) in 1984 with the density of live stems in 1986 of <u>Tamarix</u>, <u>Baccharis</u>, <u>Salix exigua</u>, and <u>Tessaria</u>.

FACTORS AFFECTING SEEDLING ESTABLISHMENT. (1) Effects of Flooding, Fluctuating Flows, and Desiccation on One-Month and Six-Month Seedlings. All treatments produced significant reductions in seedling survivorship and growth relative to control plants in both age classes and in all species (<u>Tamarix</u>, <u>Baccharis</u>, and <u>Salix</u>) (Figure 2). Our prediction that increasing levels of submergence in water (i.e., fluctuating flows or intermittent inundation as compared to complete inundation) should result in reduced survivorship and growth in all three plants was generally confirmed by the results of this experiment.

Survivorship of one-month seedlings was generally lower than that of six-month seedlings in all treatments (Figure 3). Some, though not all, of this was due to generally lower levels of survivorship in younger plants, which is indicated by the fact that survivorship was lower in the one-month-old than in the six-month-old control plants. Interestingly, lower

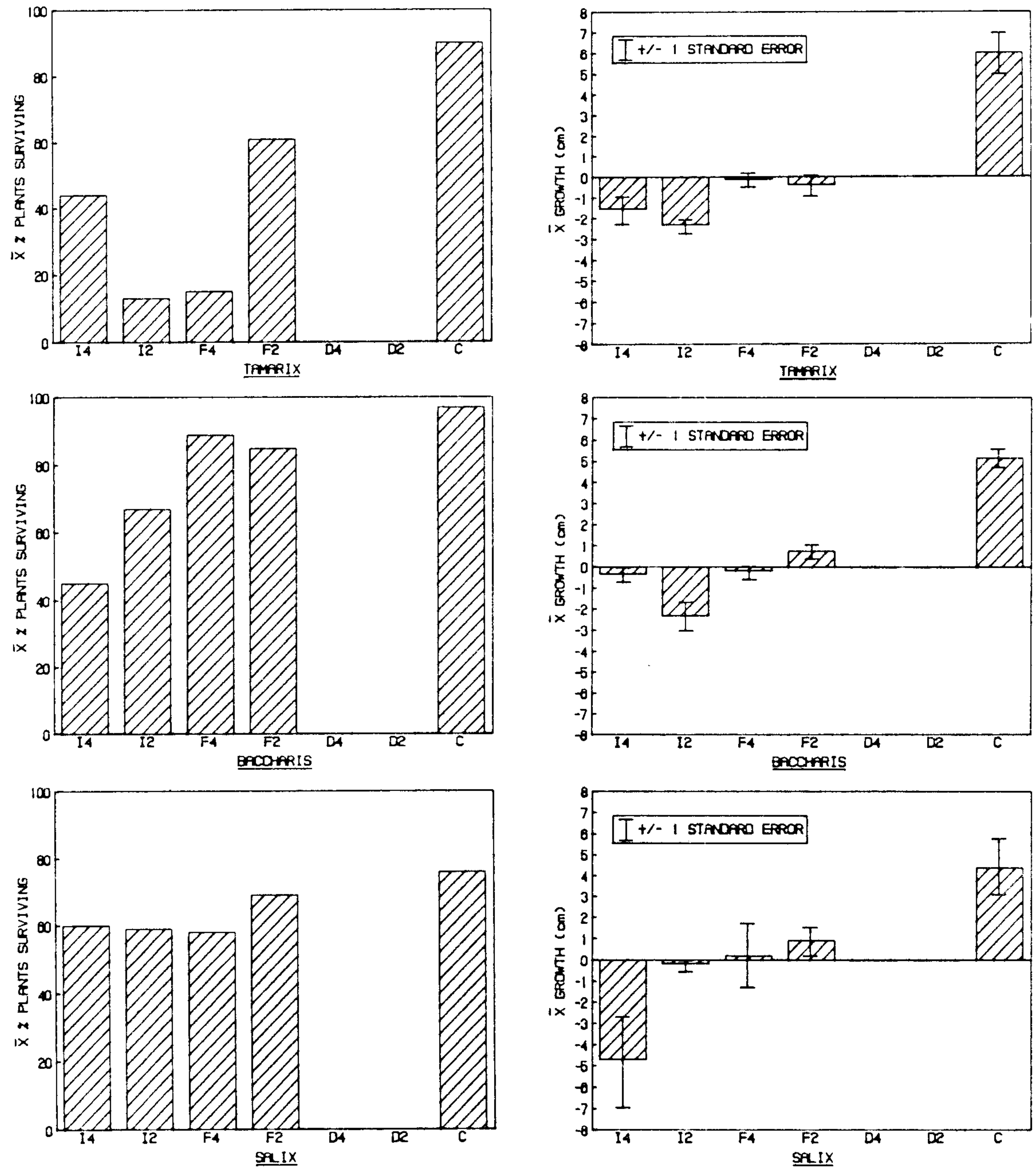

Figure 2. Mean percentage survivorship and growth (cm) of six-month-old Tamarix, Baccharis, and Salix in flooding and desiccation experiments (I4 = 4 weeks inundation, I2 = 2 weeks inundation, F4 = 4 weeks fluctuating flows, F2 = 2 weeks fluctuating flows, D4 = 4 weeks desiccation, D2 = 2 weeks desiccation, C = controls).

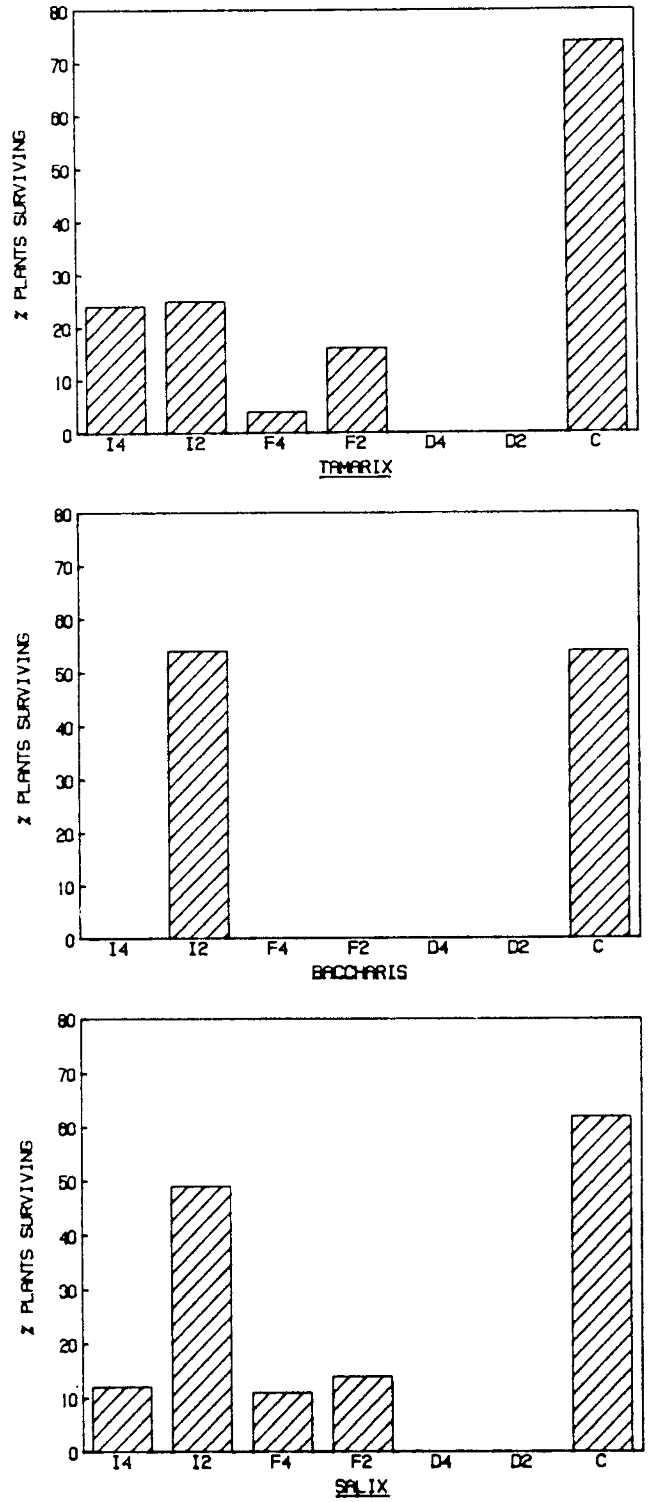

Figure 3. Mean percentage survivorship of one-month-old Tamarix, Baccharis, and Salix in flooding and desiccation experiments (I4 = 4 weeks inundation, I2 = 2 weeks inundation, F4 = 4 weeks fluctuating flows, F2 = 2 weeks fluctuating flows, D4 = 4 weeks desiccation, D2 = 2 weeks desiccation, C = controls).

levels of survivorship generally occurred in plants which underwent fluctuating (F4 or F2) treatments. We interpret this to mean that fluctuating flow disturbances remove small, shallow-rooted seedlings. While levels of survivorship were often very low, it is impressive and noteworthy that some plants did survive such harsh and protracted conditions.

(2) Effects of Substrate on Plant Germination. In experiments, survivorship for two weeks of newly germinated tamarisk and willow seedlings was high (tamarisk, mean = 96 percent on silt and 98 percent on sand, $F_{1,10}$ = 1.84, ns; coyote willow, mean = 80 percent on silt, 95 percent on sand, $F_{1,10}$ = 0.14, ns). Survivorship was not significantly different on silt versus sand substrates, indicating that, at least initially and given constant water availability, substrate type does not affect seedling colonization.

(3) Effects of Substrate on Plant Growth. In experiments, the shoots and roots of seedlings (pooled across species) grew twice as much in fine (pre-dam) versus coarse (post- dam) soil (p = 0.000, df = 1,61 for roots; and p = .000, df = 1,66 for shoots). Analysis of seedling root growth data showed significantly greater root and shoot growth rates for all species in fine (pre-dam) soils as compared to coarse (post-dam) soils (Figure 4).

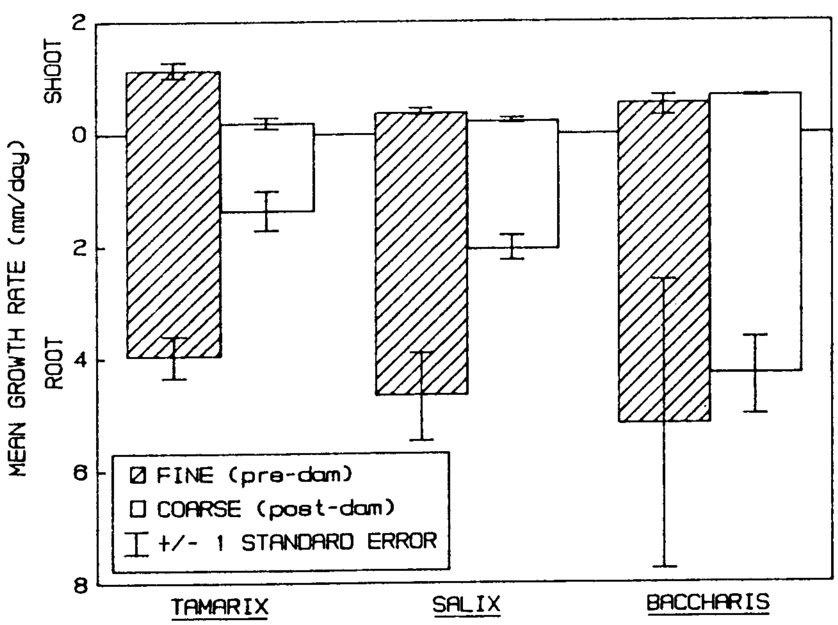

Figure 4. Mean root and shoot growth rates of Tamarix chinensis, Salix exigua, and Baccharis salicifolia in silty (pre-dam) versus sandy (post-dam) substrates. See text for statistics.

(4) Field Observations on Substrates and Plant Survivorship. We found significantly more tamarisk establishment in cobble substrates than in sand substrates at three sites which contained both substrates. Mean tamarisk seedling density was 0.42 plants/m^2 on the sand substrates and 1.20 plants/m^2 in cobble substrates ($p = 0.009$, $df = 1,234$). This pattern suggests that some aspect of cobble substrates, such as enhanced moisture retention or microsite stability, favors Tamarix establishment in cobble versus open sand.

Mortality of tagged two-year-old tamarisk seedlings was lowest (6.5 percent, n = 31) at the protected site at RM 52R, intermediate (32 percent, n = 25) in the moderately exposed rock bar at RM 131R, and highest (50 percent, n = 42) on a riverside sandbar at RM 171.5R ($X^2 = 15.64$, $p = 0.005$ at d.f. = 2). These results reflect a trend of higher mortality with increasing exposure to flooding and perhaps decreasing elevation (increasing heat stress). Mean plant growth was greatest at the protected site (12.67 cm, n = 25), intermediate at the moderate site, and lowest at the exposed site (0.02 cm, n = 21). Exposure and perhaps elevationally-imposed stress have severe effects on growth and survivorship of seedlings.

TIMING OF SEED PRODUCTION IN GRAND CANYON. The six species of perennial shrubs and small trees we studied were separated into two groups on the basis of seed production phenology: (1) those producing seeds throughout the growing season (Tamarix chinensis, Salix exigua and Baccharis salicifolia), and (2) those producing seeds only during a short interval in mid-summer (Tessaria sericea) or only in fall (Baccharis emoryi and B. sarothroides). Most reproductive output of the 13 tamarisk at Lees Ferry occurred in early summer and tapered off thereafter.

DISCUSSION

This study determined that replacement of plants lost in the 1983 flood in Grand Canyon has been a slow and localized process. For all species we studied, there was an overall decline in numbers due largely to flood-related mortality during the flood and a lack of reestablishment to date. Our results indicate two primary mechanisms that appear to be restricting plant recolonization to very specific sites or habitats within the riparian zone: (1) continued flooding since 1983, and (2) a decline in substrate quality. By understanding the role of these mechanisms, Glen Canyon Dam managers may be able to reverse this trend of plant loss in the Grand Canyon.

Most colonization in Grand Canyon is now occurring on cobble bars and, to a lesser extent, on sandy substrates. Considering that most large old stands of tamarisk in the Canyon are found in silty pre-dam sediments, this represents a dramatic shift in this species' pattern of establishment. We believe that this change is due, in part, to a loss of finer substrates (silts), an accumulation of coarse sand, and perhaps more importantly, to continued flooding which has effectively prevented colonization of most beaches by seedlings. Our seedling growth experiments demonstrated that seedlings of all species grew more slowly in sandy than in silty sediments.

Establishment of plants on cobble bar sites has been impressive. Densities of the species we studied, especially tamarisk and Baccharis spp., are approaching pre-flood densities, or, in the case of tamarisk, are actually exceeding previous numbers at some sites. Cobble or rocky substrates may slow soil desiccation, allowing colonizing seedlings to sink roots to an adequate depth before the soil dries, and cobble bars probably protect larger seedlings from being uprooted and removed by floodwaters. In contrast, sandy beaches lack such barriers against seedling desiccation and removal.

Sandy beaches are being colonized primarily by clonal species, which are reinvading from nonexposed beach peripheries via rhizomes or underground running shoots. Both coyote willow and arrowweed were found most commonly on sandy beaches. Apparently these vegetatively reproductive populations are not as susceptible as sexual, seed dispersing species to the flooding disturbance and/or rapid soil desiccation characteristic of sandy beaches.

With field experiments and observations, we have quantitatively determined the effects of flooding and desiccation on individual plants. This has helped us to account for the levels of recruitment we have observed along the Colorado River. In most cases, seedling survivorship and growth were lowest in the harshest flooding treatments. Surviving plants were very stressed, and had these plants been subjected to another bout of flooding, we predict that few, if any, would have survived. All species were very intolerant of desiccation. Both flooding and desiccation probably contributed to the fact that only about one tamarisk seedling in ten from 1984 survived to 1986, even on heavily colonized plots.

A beneficial aspect of flooding in this river system is that it permits seed germination among most riparian plant species. We have determined at what times the seeds of tamarisk, coyote willow, Baccharis spp., and arrowweed are available in the environment. These germination events play a critical role in the fate of this system, especially in the face of recurrent flooding.

CONCLUSIONS

(1) Of quadrats censused, 21 of 49 showed high levels of plant recolonization or replacement. Seedling colonization was low to nonexistent at the other 28 sites.

(2) On 15 quadrats, 1986 densities of Tamarix chinensis, Salix exigua, Baccharis spp., and Tessaria sericea approached pre-flood densities.

(3) While it is impossible to predict densities of older plants from seedling densities, large germination events are essential for replacement.

(4) Mortality and damage of six-month-old plants was greatest in the harshest flooding (inundation) treatments, while fluctuating flow treatments caused highest levels of mortality in one-month-old plants due to removal of these shallow-rooted seedlings.

(5) In the field, mortality of two-year-old plants increased from 6 percent to 50 percent with increased exposure to flooding.

(6) All plants wilted and died rapidly (within five days) when desiccated experimentally.

(7) Tamarisk and coyote willow can germinate and survive for at least two weeks in fine- or coarse-grained sediments (when adequate water is provided), but root and shoot growth rates of tamarisk, coyote willow, and seep-willow seedlings and two-year-old plants are significantly higher in fine-grained sediments. The ability to rapidly outgrow the seedling stage

should enhance a plant's ability to survive future harsh conditions of flooding or desiccation.

(8) Most post-flood establishment of tamarisk and seep-willow seedlings occurred on cobble bar substrates, perhaps because such sites offer protection from desiccation and flooding.

(9) Most post-flood establishment of clonal coyote willow and arrowweed occurred on sandy beaches as a result of reinvading runners from protected beach peripheries.

(10) A pattern of seedling reestablishment at about the 40,000 cfs zone was observed along the Colorado River, representing a shift from previous establishment of plants below that zone prior to 1983.

(11) Seeds of tamarisk, *Baccharis salicifolia*, and coyote willow are produced throughout the growing season, while seeds of arrowweed, *B. emoryi*, *B. sarothroides*, *Brickellia* sp., acacia, mesquite, and cottonwood are produced only during brief periods in the growing season.

(12) Seep-willow and coyote willow seeds are produced continuously throughout the growing season, while most tamarisk seeds are produced early in the growing season.

RECOMMENDATIONS

A baseloaded or relatively constant flow regime is preferred for this riparian plant community because recruitment and recovery occur faster in a disturbance-free environment.

Extreme fluctuating flows would negatively affect riparian plant community development by damaging existing plants and by retarding recruitment in the floodzone nearest the river, where riparian vegetation could be the most profuse.

TIMING OF SPILLOVERS. Although flooding disturbance promoted germination, our studies indicate that post-dam flooding from 1983 to the present has had a negative impact on overall riparian plant community development in the Colorado River corridor in the Grand Canyon. Because recovery may require a decade or more, erratic releases should be avoided in this system if at all possible. If spills are necessary in the future, we suggest that they be restricted in amplitude and duration as much as possible. At present, we predict that duration of flooding exerts a greater effect on survivorship than does amplitude, but this question deserves more study. A late summer or fall flood could be used to disperse seeds of native riparian species (as opposed to tamarisk), thereby increasing riparian plant diversity.

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EFFECTS OF THE POST-GLEN CANYON DAM FLOW REGIME ON THE OLD HIGH WATER ZONE PLANT COMMUNITY ALONG THE COLORADO RIVER IN GRAND CANYON

The goal of this study was to determine if the Old High Water Zone community would become senescent under the post-dam flow regime and to determine the effects of floods and fluctuating flows on seedling establishment and survivorship.

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INTRODUCTION

The Colorado River in Grand Canyon, with 275 miles of protected riparian habitat, represents the longest contiguous protected riparian corridor in the western United States. The two overwhelmingly dominant native tree species in the Colorado River riparian zone are western honey mesquite (*Prosopis glandulosa*) and catclaw acacia (*Acacia greggii*). They form the Old High Water Zone (OHWZ), which was the major pre-dam riparian community. This community is an important component of the Grand Canyon ecosystem. It provides nesting sites and foraging substrate for birds (Brown and Johnson 1987), cover for reptiles and amphibians (Warren and Schwalbe 1987), and breeding sites and food sources for insects (Stevens and Waring 1987). In addition, mesquite and acacia pods provide an abundant food source rich in carbohydrates and protein that is an important item in the diet of many insects and mammals. For these reasons, any reduction in the extent or vigor of OHWZ vegetation will have impacts on many other components of the Grand Canyon ecosystem.

Formation and dynamics of the OHWZ riparian community appear to be related to water availability and flood frequency. Historically, the lower boundary of perennial vegetation was determined by the scouring line of floods, below which plant establishment could not occur (Carothers et al. 1979; Turner and Karpiscak 1980). The upper boundary appears to have been determined by two major factors. Most important was the level of soil saturation by pre-dam annual floods, which provided moisture for a sufficient duration to allow successful germination and establishment of seedlings. A second factor has been the availability of suitable soil to support stands of perennial riparian plants.

There are several potential impacts of post-dam flow release patterns on the OHWZ. Possibly the most important is the reduction of available soil moisture in the late spring and summer due to the elimination of pre-dam seasonal floods. Before construction of Glen Canyon Dam, high late-spring floods from snowmelt had several important effects. They provided moisture during the flowering and fruiting season to mesquite and acacia located high on the shore above normal river levels. High water also moistened the soil prior to seed germination in midsummer, which may have increased germination success. These early summer floods were extremely important because they occurred during the dry season when moisture was not available from precipitation. Later floods from summer rains may have had some importance in keeping seedlings alive. In addition, spring and summer pre-dam floods also carried high sediment loads that may have been important in replenishing nutrient levels of shoreline soils. The low sediment load of post-dam flows could lead to a decrease in soil nutrient levels, which would affect vigor of both adult and seedling trees. If the increased sediment carrying capacity of post-dam flows results in erosion of beach and terrace areas in the New High Water Zone (NHWZ), the riparian community along the river's edge, this could reduce the area available for colonization by seedling mesquite and acacia.

OBJECTIVES

The overall objective of this study was to determine whether dam-controlled river flows in the Colorado River have been deleterious to the health of OHWZ riparian tree populations in the Grand Canyon. This research was prompted by the major question: are mesquite and acacia in the OHWZ community dying out? Because the extremely high flows in 1983 watered much of the OHWZ community with overbank flows for the first time in more than 20 years, one aspect of this study was designed to compare growth in 1983 with that in subsequent years in an attempt to determine the effects of flooding. To determine whether or not a community is senescent, all aspects of the life history of the dominant species should be examined. Therefore, this study was divided into four major parts:

(1) Adult growth was measured to determine the general vigor of adults. Comparisons between river and adjacent tributary sites were made to distinguish between the effects of river flow

regimes and those of local climatic factors such as precipitation and temperature. In particular, we wanted to know if adult growth varies between years with different flow regimes, especially years with very high flows similar to pre-dam levels, versus those with the lower, steady and fluctuating flows characteristic of the post-dam river.

(2) Age class distribution was censused to determine the age class structure of mesquite and acacia and to determine whether there are differences in the distribution of age classes across habitats and soil substrates. In particular, we want to determine where reproduction is successful and whether mesquite and acacia are replacing themselves in the OHWZ community or moving into the NHWZ.

(3) Tagged seedlings and saplings were followed to determine the effects of flooding, fluctuating flows, and steady flows on survivorship of different age classes. Germination success in experimental plots at different distances from the river was measured to determine the effect of river flows on seedling germination and establishment, and to establish populations for long-term monitoring as flows change.

(4) Adult reproductive effort and success were measured in several ways. At the population level, the proportion of trees flowering at each site and the phenology of flowering were censused to determine whether the number of trees flowering and successfully fruiting varies along the river corridor. At the individual level, the number of flowers, fruits and seeds produced were measured to determine the effort expended at each stage of flowering and how fruit production in Grand Canyon compares to other locations documented in the literature. In addition, seed predation, abortion, and viability were compared at different sites along the river corridor to assess fruiting success.

Mesquite and acacia are long-lived trees and the effects of the post-Glen Canyon Dam flow regime may take time to manifest themselves. Therefore, the studies initiated as part of this project have been designed for long-term monitoring as well as to provide the short-term results presented here. In general, adults are likely to be affected by large or long-term changes in river flows, but will probably not be affected by daily fluctuations in flows. Seedlings and saplings are likely to be affected by short-term changes in river flows, such as daily fluctuations, as well as longer-term changes such as spring flooding.

METHODS

Each of the four major components of the study were replicated at a series of locations along the river corridor in Grand Canyon. This was done because variation in geologic substrate, landform, and local climate in different river reaches might significantly affect riparian tree growth and reproduction. This study was begun in June 1984 and continued through September 1986.

ADULT GROWTH. One site in each of the four reaches of the river in Grand Canyon was chosen for monitoring adult growth. Reach 1 is from Lees Ferry to the Little Colorado River; Reach 2, from the Little Colorado to Bright Angel Creek; Reach 3, from Bright Angel Creek to National Canyon; and Reach 4, from National Canyon to Diamond Creek. The sites were chosen on the basis of two criteria: (1) presence of large, dense stands of mesquite and acacia in the OHWZ, and (2) presence of stands of mesquite or acacia in tributaries adjacent to OHWZ study sites. Tributary sites served as controls to compare growth of mesquite and acacia under the influence of ambient precipitation with OHWZ trees under the influence of river flows.

Mesquite adults were selected for growth studies at all sites except in Reach 4, where mesquite is not present. We emphasized mesquite over acacia because, unlike acacia, it is restricted to riparian areas and therefore was expected to show a greater dependence on river flows.

Forty trees were selected for growth measurements at each site: 20 in the OHWZ and 20 in the adjacent tributary. Twenty shoots were measured per tree. A dendrometer was placed on each tree to measure radial stem growth, an overall indicator of tree vigor. The dendrometer does not interfere with growth, and since it remains on the tree, radial growth can be measured over long time periods. Each numbered dendrometer also marked individual trees for relocation in subsequent years.

Patterns of radial growth over longer periods of time were determined by measuring the width of annual growth rings on selected individuals. Narrow wedges were cut from healthy trunks of seven acacia and five mesquite without severely damaging the trees. Mesquite did not show identifiable growth rings and could not be dated or measured. However, acacia did show recognizable annual growth rings. Trunk sections were dated by Dr. C. W. Ferguson, of the Tree-Ring Laboratory, University of Arizona, and annual growth increments were measured by Dr. B. Kincaid, of the Department of Botany/Microbiology, Arizona State University.

AGE CLASS DISTRIBUTION. Age class surveys were conducted by censusing belt transects that were oriented parallel to the shoreline. Mesquite and acacia were divided into four age classes: seedlings, saplings < 5 years of age, saplings > 5 years of age, and adults. The NHWZ was further subdivided into two zones: one below the 50,000 cubic feet per second (cfs) line and one above the line. Age class surveys were done in each of the two subdivisions. All seedlings and some saplings were tagged to monitor survivorship. A total of 215 age class survey transects were censused in the NHWZ and OHWZ at 73 sites over the course of the study.

SEEDLING AND SAPLING SURVIVORSHIP. Seedlings and saplings were tagged with aluminum tags during age class surveys. In all, 424 mesquite and 317 acacia seedling and saplings were tagged. An attempt was made to relocate tagged individuals at least once each year; however, approximately half the tagged individuals were not found again.

ADULT REPRODUCTIVE EFFORT AND SUCCESS. Studies of reproductive effort concentrated on mesquite for two reasons: (1) Mesquite are obligate riparian trees and should be most sensitive to post-dam flow regimes. (2) Many fewer mesquite seedlings were found than acacia seedlings; therefore, we were particularly interested in determining in what portion of the life cycle (flowering, fruiting, seed production, seed viability, or germination) the breakdown in mesquite reproductive success occurred. If these studies continue, we hope to gather comparative data for acacia.

Flower phenology of mesquite populations was surveyed along belt transects similar to those described for age class distribution. Thirty-six phenology surveys were done in the OHWZ at 24 sites from May to August 1986. The density of inflorescences in different flowering stages was measured for 135 trees at 13 sites.

Inflorescences were counted and recorded as buds, full blooms, past blooms (flowers had dried up or fallen off the rachis) and fruits on eight branches per tree, all of which were marked with aluminum tags. In addition, the number of fruits/ inflorescence and seeds/fruits were counted.

Rates of seed predation and abortion were measured for 288 fruits from 29 trees at seven sites. Seeds were removed from the pod, and good seeds, aborted seeds, and those that had been subject to predation were counted. The major seed predator was a bruchid beetle (Algarobius prosopis Cleconte) (Stevens, pers. comm.). Predated seeds were recognized by a hole bored in the seed coat and in several cases the presence of the larvae. Aborted seeds were much smaller and darker than normal seeds and were either flattened or shriveled.

Fifty to 100 good seeds were tested from each tree to determine viability. Seeds were scarified by nicking the seed coat opposite the micropyle end. Seeds were soaked for one hour, then placed in petri dishes on wet filter paper. Seeds were recorded as germinated once the root had broken through the micropyle end. Of the seeds that germinated, 98 percent did so in the first 24 hours, though seeds were observed for 48 hours.

Two experimental plots were established, one at Nankoweap (River Mile [RM] 53R) and one at Granite Park (RM 209L), to test germination and survivorship success of scarified seeds. Seeds were soaked overnight, then planted in groups of three at 1 m intervals along three transects placed at the 30,000 cfs, 50,000 cfs, and 90,000 cfs river flow levels, for a total of 300 seeds/transect and 900 seeds/plot. The plots were resampled one month after planting to determine seedling establishment.

RESULTS AND DISCUSSION

ADULT GROWTH AND MORTALITY. Mesquite and acacia showed vigorous shoot growth in all years sampled. Growth in river sites was not significantly different from growth in tributary sites uninfluenced by river flows (Table 1). Nor was growth during the 1983 season of high flows significantly greater than growth during the other three years. Contrary to expectations (if high flows do benefit the OHWZ), regression analysis showed no positive correlation (r) between shoot growth of riparian trees and maximum river flow levels.

Table 1. Mean total shoot growth/tree mesquites at each site compared across habitats (river vs. tributary sites). Means with the same subscript are not significantly different by one-way ANOVA and Tukey's test of means at p<.05.

Site	River				Tributary				F	P
	1983	1984	1985	1986	1983	1984	1985	1986	Value	
Mesquite										
Nankoweap (RM 53)	442 *	472 *	476 *	283 !$	464 *	493 *	346 *!	160 $	11.1	<.001
Unkar (RM 72)	517	513	383	395	484	550	554	376	2.0	NS
Granite Park (RM 209)	504 *	363 !	386 !*	281 !	379 !*	450 *	500 *	410 *	6.0	<.001
Acacia										
National Canyon (RM 167)	363	267	256	325	344	278	351	295	1.8	NS

It appears that adult growth may be independent of river flows; however, it must be taken into account that flows during the four years of the study have been consistently above "normal" post-dam levels (Table 2). Several factors have contributed to these elevated flows. High snowmelt runoff in 1983 filled Lake Powell and led to extremely high releases which were similar to pre-dam river discharges, with high to moderate floods in the late spring tapering off through late summer and winter. Floods have continued, and are likely to do so as long as winter precipitation remains above normal and Lake Powell is full. Although none of the regressions were significant, mesquite growth in river trees for all reaches did show a weak trend toward a decline in growth from a high in 1983 to a low in 1986 (Table 1). The fact that no such trend was observed in tributary trees emphasizes the declining trend in growth of river trees. This indicates that differences in growth between river and tributary trees may be more apparent in a year without high spring river flows.

Sharifi et al. (1983) reported that shoot elongation was the character most highly correlated with water

Table 2. Highest river flow levels (in cfs) for the year, averaged over the month of highest flows and averaged over the growing season (March-October).

Year	Highest Flow of the Year	Mean Highest Daily Flow/Month of Highest Flows	Mean Highest Daily/Flow/ Growing Season
1983	93,200	60,006 (June)	39,006
1984	44,069	41,662 (June)	35,920
1985	45,613	40,418 (May)	29,791
1986	48,034	42,553 (May)	30,570

availability and moisture stress in mesquite in the Sonoran Desert of California. Based on physiological measurements made during the dry season, they determined that the southern California trees had roots reaching the permanent water table. The similarity in mean shoot elongation between Californian and Grand Canyon trees implies that trees in Grand Canyon also have roots reaching permanent water. If this is the case, fluctuations in river flow levels may not have as strong an effect on growth of adults as originally expected.

Evidence from tree-ring analysis of acacia indicates that there has been a long-term effect of Glen Canyon Dam on growth of acacia. Annual growth rings were counted for five acacia individuals, four along the river and one in a tributary site. A 20-year period of post-dam growth (1964-1983) was compared with two equal periods of pre-dam growth (1923-1943 and 1944-1964) (Table 3). In all the river trees, growth in the post-dam increment was smaller than in either of the pre-dam periods. Mean growth for these periods was significantly different in two of the four trees. The tributary tree, the oldest of all trees sampled, had greater growth after construction of the dam than during either pre-dam period. This observation was surprising, since older trees usually grow more slowly than young trees, and emphasizes the significance of the reduction in post-dam growth of river trees sampled. Tree-ring analysis of elm, ash, and oak along the Missouri River in North Dakota has shown a similar trend of post-dam decreases in growth after the establishment of the Garrison Dam in 1953 (Reily and Johnson 1982).

Table 3. Sixty years growth of five catclaw acacia along the Colorado River in the Grand Canyon determined by tree-ring analysis. Growth increments are in mm. Means with the same symbol beside them are not significantly different by one-way ANOVA and Tukey's HSD Test at p<.05.

	Tree Location				
	Nankoweap Top OHWZ	Nankoweap Lower OHWZ	Unkar Lower OHWZ	National Lower OHWZ	National Tributary
1924-1943					
Total	-	12.01	19.48	23.08	8.00
Mean	-	0.60*	0.97*	1.15*	0.40*
1944-1963					
Total	18.24	12.38	21.61	15.43	7.91
Mean	0.91*	0.70*	1.08*	0.77*!	0.40*
1964-1983					
Total	16.86	10.95	8.33	14.98	9.24
Mean	0.80*	0.52*	0.40!	0.71!	0.44*
Age (yrs.)	45	65	65	81	100
F Value	NS	NS	22.4	3.92	NS

Though high spring dam releases may slightly improve shoot growth in river trees, high flows, especially very high flows like those of 1983, also lead to increased mortality of mesquite adults in the NHWZ. Mesquites closest to the river below the 50,000 cfs line have higher percent mortality than do mesquites away from the river's edge or in the OHWZ (Anderson and Ruffner 1987).

Aerial photo analysis of the OHWZ indicates a reduction in the extent of mesquite and acacia from 1963 to 1985 (Pucherelli 1987) and may reflect either reduced growth rates and/or increased mortality under the post-dam flow regime. The reduction in the extent of OHWZ species was greatest in the upper, cooler reaches of the river (Pucherelli 1987) and may also be the result of severe freezes in 1979 and 1984. Mesquite responds to freezing with canopy die-back, but often resprouts from the base (pers. obs.).

SEEDLING ESTABLISHMENT AND SURVIVORSHIP. Establishment and survivorship of seedlings appears to be affected more by short- and long-term changes in river flow patterns than does growth in adults. The most striking change in the community is the establishment of acacia and mesquite in the NHWZ since the completion of Glen Canyon Dam. In fact, most of the seedlings and saplings of acacia and mesquite were found in the NHWZ (Figure 1). Subadult mesquite in the OHWZ are rare, indicating that ambient precipitation is too low to support seedlings away from the influence of river flows. Subadult acacia are found in much greater numbers than subadult mesquite in all riparian habitats, outnumbering them by 19:1.

However, mortality of acacia is higher than that of mesquite across all age classes (Figure 2). For both mesquite and acacia, seedlings have the highest mortality of all age classes. Saplings three-five years old also have relatively high mortality. The three-five year cohort is composed of many individuals that germinated during the high flows of 1983. Increased mortality in this age class may be the result of seedlings that germinated at water's edge during high flows and were later stranded. Once dam releases were lowered, soil moisture in the upper NHWZ decreased, possibly resulting in greater desiccation mortality for this cohort of saplings.

Mortality for subadult mesquite and acacia is higher in the OHWZ than in the NHWZ (Figure 3). Mesquite shows proportionally a much greater increase in mortality from the NHWZ to the OHWZ, perhaps reflecting lower drought tolerance for subadult mesquite than for subadult acacia.

REPRODUCTIVE EFFORT OF ADULT MESQUITE. The study of mesquite reproductive effort was motivated by the question: why are there so few mesquite seedlings and saplings in both the old and new riparian zones? A breakdown in reproduction could come at any phase in the reproductive cycle. Adults may not flower; flowers may not become fruits; fruits may not mature; seeds may not be viable; seedlings may not become established.

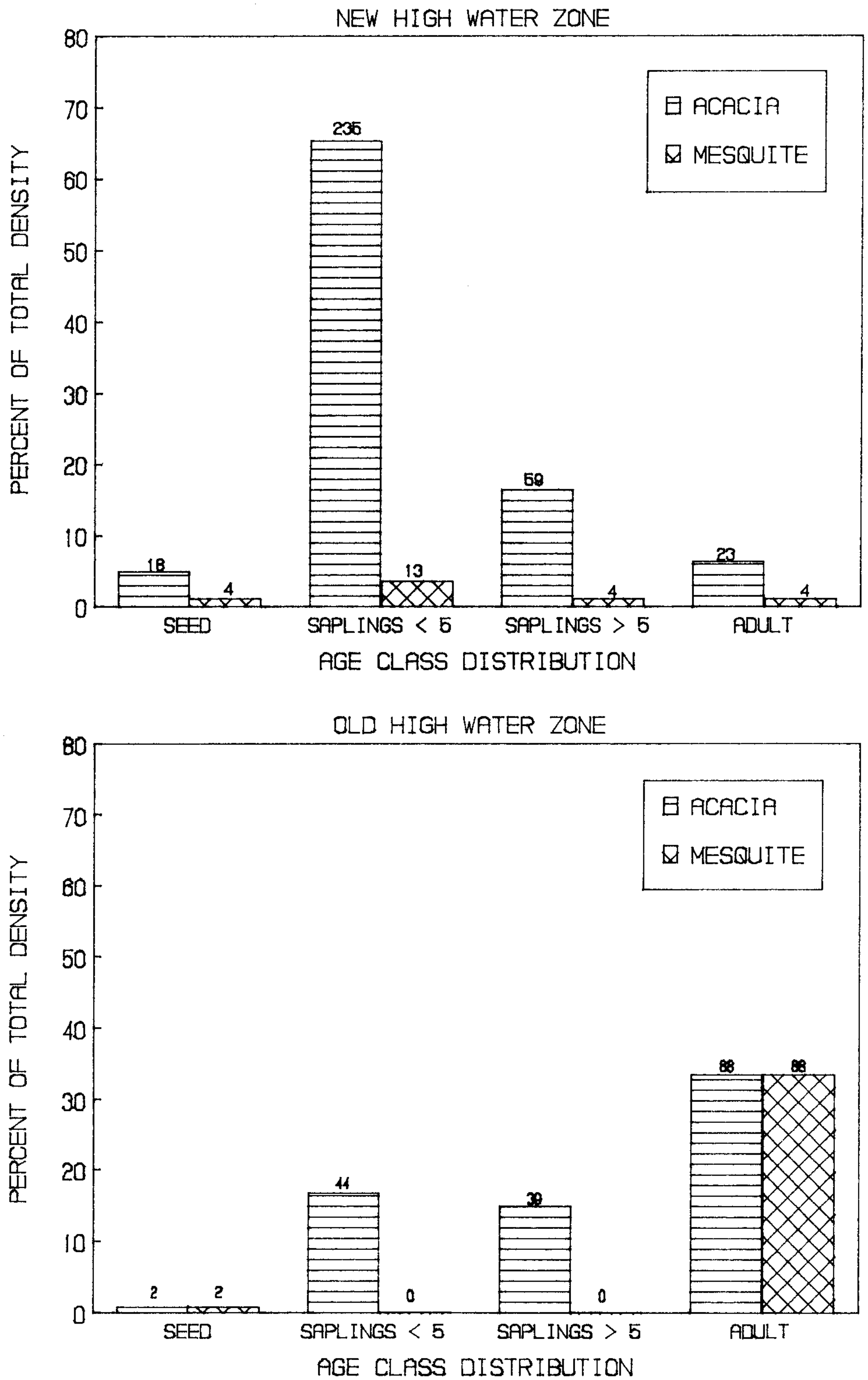

Figure 1. Age class distribution of mesquite and acacia in the New High Water Zone and Old High Water Zone.

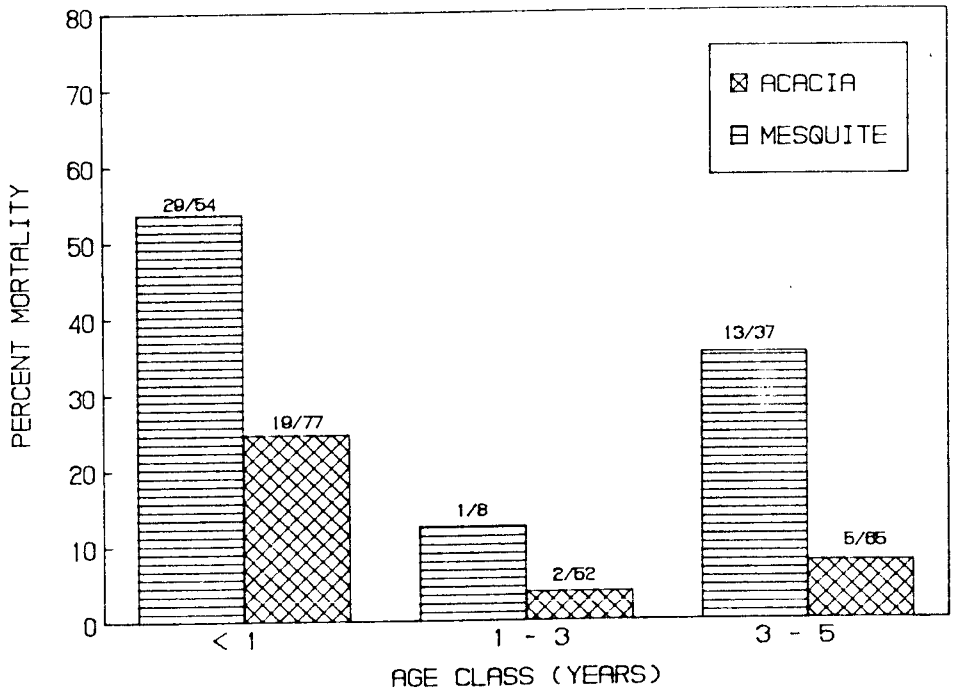

Figure 2. Percent mortality of different age classes of tagged mesquite and acacia.

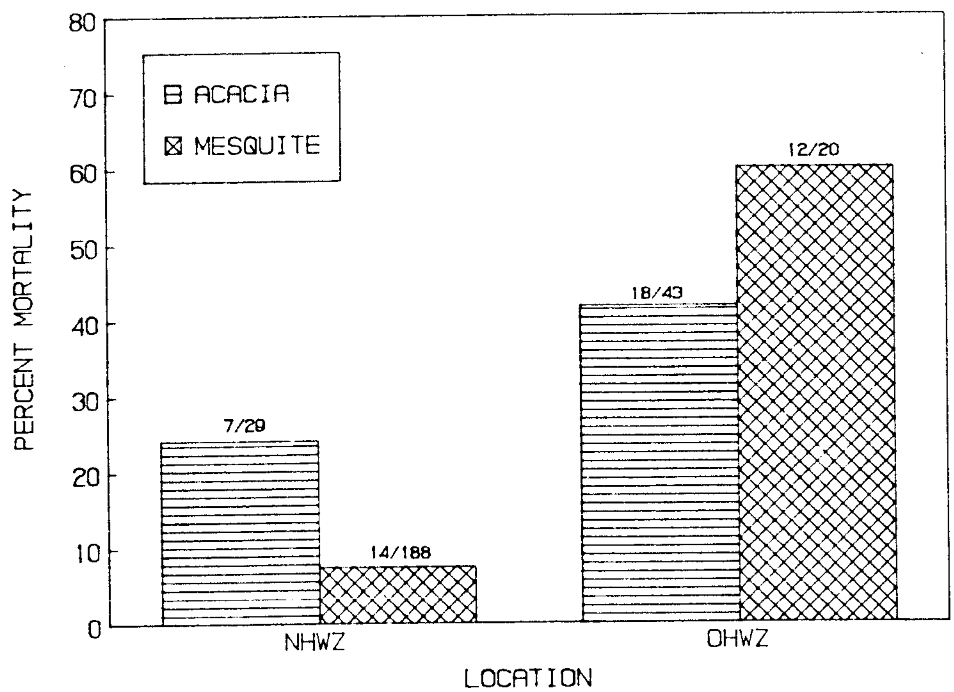

Figure 3. Percent mortality of seedlings and saplings in the NHWZ and the OHWZ.

Not only are adults growing vigorously in the OHWZ, but some members of each population are flowering and producing fruit. Flowering phenology at the population level showed that 30-65 percent of the mesquite bloomed at each site and 4-20 percent of the trees produced fruit. When individual inflorescences were followed, between 30-43 percent were found to produce fruit. Though only 30 percent of the trees surveyed in Reach 5 bloomed this year, Reach 5 had the highest mean fruits/inflorescence and the highest number of fruits/tree, which compensated somewhat for differences in blooming at the population level. The viability of seeds was uniformly high (96 percent) for scarified seeds. Unscarified seeds have lower viability (75 percent) and take much longer to germinate (Stevens, pers. comm.). However, results of experimental planting show that seedling establishment is low and is concentrated on the river's edge. After one month, less than 4 percent of all seeds planted in the field trial survived as seedlings (Table 4). A dramatic decline in germination occurred away from the wetted soil near the river's edge.

Table 4. Seedling survival after one month in experimental plantings at different distances from the river. Seeds were planted at the river flow lines for 30,000 cfs, 50,000 cfs and 90,000 cfs.

Site	Transect Location	# Seeds Planted	# Seedlings Surviving	# Dead Stems
Nankoweap (RM 53R)	30,000 cfs	300	17	0
	50,000 cfs	300	0	0
	90,000 cfs	300	0	0
Granite Park (RM 209L)	30,000 cfs	300	31	2
	50,000 cfs	300	2	7
	90,000 cfs	300	0	0

CONCLUSIONS

The adverse effects of managed river flow regimes should be greatest on seedlings. Seedlings rely on the wetted soil near the river's edge for germination and establishment. This has both short- and long-term consequences. In the short-term, seedlings and saplings run a greater risk of mortality from dam releases than other age classes. If dam releases vary from week to week, seedlings that germinate near the river's edge when dam releases are low will be inundated and die as flows rise. Seedlings that germinate when dam releases are high may suffer desiccation and die when river flows drop. In the long-term the extent of mesquite and acacia in the NHWZ will depend on patterns of seedling establishment and survival. As in the past, before construction of Glen Canyon dam, survival will depend on the height of spring floods. Mesquite and acacia will persist in the NHWZ; in fact, both species already have reproducing adults in the new zone.

Short-term changes in dam releases, such as fluctuating flows, probably will have little effect on adult mesquite and acacia in the OHWZ. The long-term effects of post-dam flows on these adults is difficult to determine. Tree-ring analysis of acacia implies a decrease in growth rates under post-dam flows. In addition, the lack of young age classes of mesquite in the OHWZ may lead to the movement of that species into the NHWZ. However, mesquite are very long-lived and seedling recruitment may only need to occur rarely for mesquite to persist in the OHWZ. Acacia is likely to persist in the OHWZ because it is more drought tolerant than mesquite and not restricted to riparian zones in the Grand Canyon. With post-dam flows, the OHWZ is becoming more xeric, and acacia may become the dominant tree in that zone.

RECOMMENDATIONS

Dam releases that do not exceed 31,500 cfs will not directly affect mesquite and acacia in either the OHWZ or NHWZ. Seedling establishment of mesquite and acacia will occur down to the line of highest flow. If there are no spring floods, the community will extend to the level of highest operations, 31,500 cfs. Daily fluctuations in river levels are not likely to directly affect distribution of mesquite and acacia as long as peak capacity is reached each day during late summer and fall. This will allow seedling germination to occur where seedlings are most likely to survive.

Over the long-term, however, nutrient leaching and erosion of riparian substrate could have significant, deleterious, long-term effects on the vigor and extent of existing OHWZ vegetation and on establishment of OHWZ species in the NHWZ. Both nutrient leaching and beach erosion appear to increase dramatically after flooding (Stevens and Waring 1987; Schmidt and Graf 1987). Seedling and sapling density is greatest in tributaries and alluvial tributary deltas characterized by silt and streambed cobbles. This indicates that seedling establishment may be sensitive to nutrient levels. Since nutrient leaching appears to be an irreversible effect due to the reduced sediment load below Glen Canyon Dam, selection of a flow regime that reduces the rates of nutrient leaching and beach erosion is particularly important. Management alternatives that minimize leaching of shoreline soils and erosion of beaches should be favored.

Adult growth of acacia and mesquite in the OHWZ did not increase markedly after the high water in 1983. This indicates that periodic high floods do not have a strong positive effect on growth. In addition, high floods result in high mortality of individuals in the NHWZ. Though periodic floods may open areas for seedling colonization, the balance between sapling mortality and new establishment is unknown. The inundation survival threshold for mesquite and acacia is also unknown. Given the evidence of increased mortality from floods and the lack of evidence for increased establishment, we would recommend against periodic flooding as a management alternative.

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THE EFFECTS OF FLUCTUATING FLOWS ON BREEDING BIRDS

This study examined the effects of the operation of Glen Canyon Dam on riparian breeding birds of the Colorado River. The research objectives addressed rates of nest inundation, bird density and diversity in different habitats, nesting habitat choice, and long-term population changes.

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INTRODUCTION

The breeding birds of the Colorado River corridor have been greatly influenced by the construction and operation of Glen Canyon Dam. The dam has had mainly an indirect, positive influence on birds by creating new areas of riparian habitat in the pre-dam scour zone. Beginning in 1963, the dam prevented flooding which historically had scoured away any vegetation below the pre-dam high water line. The resulting new habitat, dominated by introduced tamarisk shrubs, was colonized by riparian breeding birds over the next decade. Several species of birds expanded their breeding ranges upriver to take advantage of the new habitat. However, in 1980, Lake Powell reached maximum storage capacity for the first time, and a series of large surplus water flows which approximated pre-dam flood conditions was released from the dam. This led to a need to modify the operating criteria of Glen Canyon Dam and to management concern over the future well-being of breeding birds in the river corridor.

OBJECTIVES

This study was designed to explore the relationships between the operation of Glen Canyon Dam and breeding birds of the Colorado River in Glen Canyon National Recreation Area downstream from the dam and in Grand Canyon National Park. The purpose was to identify the effects of fluctuating flows, as well as those occasional surplus water releases above 31,000 cubic feet per second (cfs), on birds that nest in the riparian zone of the river corridor.

The relationship between fluctuating flows and breeding birds was examined in the framework of four primary objectives:

(1) The number of active nests inundated at various flow levels was documented for each species. Inundation rates showed which bird species were most likely to be directly influenced by fluctuating flows.

(2) The density and diversity of breeding birds were measured in both the mesquite-dominated Old High Water Zone (OHWZ) and tamarisk-dominated New High Water Zone (NHWZ). Density and diversity information illustrates the relative importance of these two major habitat zones to the overall riparian bird community. This is particularly important if fluctuating flows are causing long-term changes in either zone.

(3) The nesting habitat preferences of obligate riparian birds in the NHWZ were documented and compared. Obligate riparian birds nest only in riparian habitat and are therefore most sensitive to long-term habitat changes that could result from fluctuating flows.

(4) The population density of five indicator species of birds was determined from 1982 to 1986 to reveal population fluctuations that may have been influenced by Glen Canyon Dam.

METHODS

We located nests of riparian birds throughout the river corridor from 1982 to 1985. Information on the timing of nesting and nest heights relative to both the ground and the surface of the water were taken for each nest. Flow levels that would inundate specific nests were calculated, based on nest heights and on flow rate and gage height information supplied by the U.S. Geological Survey for the Lees Ferry and Phantom Ranch (Near Grand Canyon) gaging stations. Much of the inundation data were gathered during the surplus water release of over 92,000 cfs in June 1983. This large release allowed the direct measurement of water levels at many nests that had been located and mapped in 1982 and early 1983.

Breeding birds were censused from 1984 to 1986 at ten study sites between Glen Canyon Dam and Diamond Creek.

Each study site consisted of paired study plots, one each in the OHWZ and NHWZ. We used the absolute count method, a census technique by which the observer counts all birds seen or heard in small linear study sites (Emlen 1971). The number of pairs of birds at each study plot was then transformed to numbers of pairs/40 ha, the standard unit of measurement in reporting avian densities. Avian densities in the OHWZ and NHWZ were statistically compared using the Wilcoxon signed rank test.

Discriminant function analysis, a multivariate statistical technique, was used to compare the nesting habitat preferences of obligate riparian birds in the NHWZ. Habitat use was analyzed for only the NHWZ since it was the zone most influenced by fluctuating flows. Also, most obligate riparian birds nested primarily or exclusively in the NHWZ. Ten variables representing vegetation structure and shrub species composition were measured in 0.04 ha circles centered at nest sites. The raw data for each of these variables were mathematically transformed and statistically analyzed. The results indicated the relative habitat preferences of each species within three-dimensional "habitat space" represented by a habitat model.

The population densities of five indicator species of obligate riparian birds were determined from 1982 to 1986 using an indirect count census (Schemnitz 1980). The indirect count, or call count (Bull 1981), is a true census of the number of singing male birds heard on an 18-day, oar-powered raft trip between Lees Ferry and Diamond Creek at the height of the breeding season for each species. This census resulted in an index to the population densities of the five species under study. An index is a census of some variable (in this case, bird songs) related to the true number of animals being studied, which reliably identifies changes in annual density. Singing male birds were counted primarily from 0800 to 1200 hours each morning as the boats floated downstream. The five indicator species were chosen because: (1) they are all highly vocal at the peak of the breeding season, and (2) they represent a wide range of abundance, distribution, and habitat use patterns--a combination representing most of the variability exhibited by the entire riparian breeding bird community.

RESULTS

Fluctuating flows of up to 31,000 cfs had little direct effect on breeding birds. At this release level, only a single black-chinned hummingbird nest was known to have been inundated, representing less than 1 percent of the population of that species in the river corridor.

Surplus water releases above 31,000 cfs inundated substantial numbers of bird nests, primarily those of the common yellowthroat, Bell's vireo, and yellow-breasted chat. These three species were most susceptible to nest inundation because their nests were located both closest to the water's edge and lowest to the ground. Surplus water releases up to 40,000 cfs inundated approximately 90 percent of all common yellowthroat nests; releases above 40,000 cfs began to inundate substantial numbers of Bell's vireo and yellow-breasted chat nests (Figure 1). Small numbers of the nests of other species were inundated, including those of black phoebe, Say's phoebe, and violet-green swallow. The surplus water release of June 1983 coincided with the May to July peak of breeding for most species, causing a higher inundation rate of active nests.

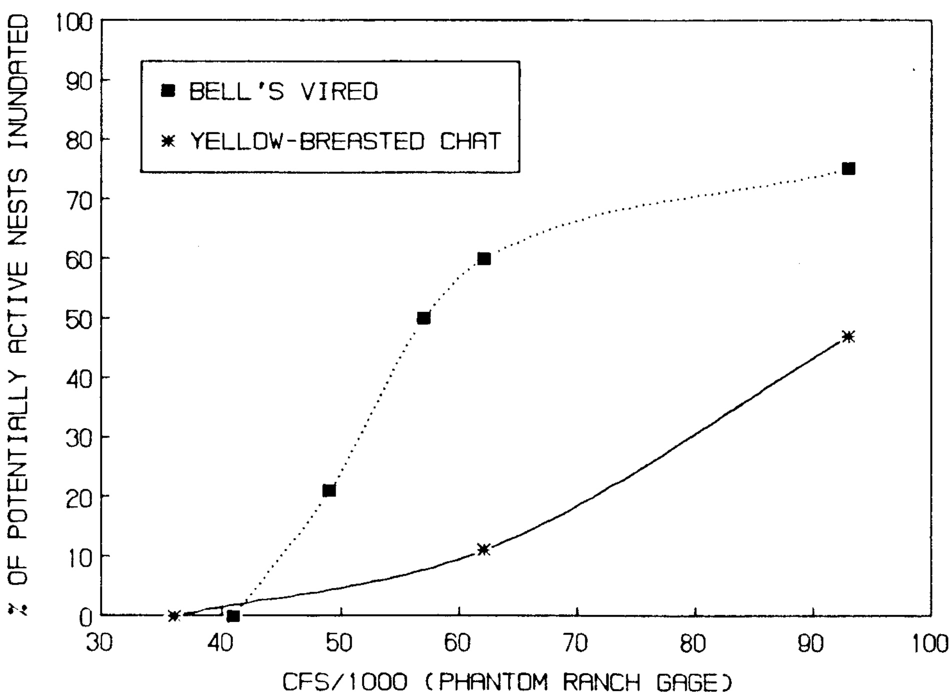

Figure 1. Percent of nests inundated at various release levels, June 1983. Symbols represent known data points.

Tamarisk habitats in the NHWZ exhibited a significantly higher density of breeding birds than mesquite habitats in the OHWZ (Table 1). The density of breeding birds in several well-developed riparian areas of each zone exceeded 800 pairs/40 ha and therefore ranked among the highest densities ever reported for non-colonial breeding birds in North America. Avian diversity was similar in both zones.

The 11 species of obligate riparian birds known to breed in the NHWZ differed in their choice of nesting habitat, both in the range and type of habitats chosen. Figure 2 identifies the relative nesting habitats

Table 1. Breeding bird density (pairs/40 ha) in OHWZ and NHWZ sites along the Colorado River in Glen and Grand Canyons, 1984-1986.

Site Number	Location	1984 OHWZ	1984 NHWZ	1985 OHWZ	1985 NHWZ	1986 OHWZ	1986 NHWZ
01	Glen Canyon/ Lees Ferry	318	441	200	552	282	338
02	Saddle Canyon	538	486	300	571	388	371
03	Cardenas Canyon	747	941	613	824	1000	717
04	Lower Bass Camp	200	500	300	100	200	200
05	Forster Canyon	200	400	200	400	200	250
06	National Canyon	182	600	73	300	109	300
07	Stairway Canyon	565	857	529	1085	565	771
08	Parashant Wash	986	1200	943	1200	514	480
09	Granite Park	357	480	229	220	182	320
10	220-Mile Canyon/ Granite Springs Canyon	400	200	400	400	556	200
Mean Density		449	611	379	565	400	395

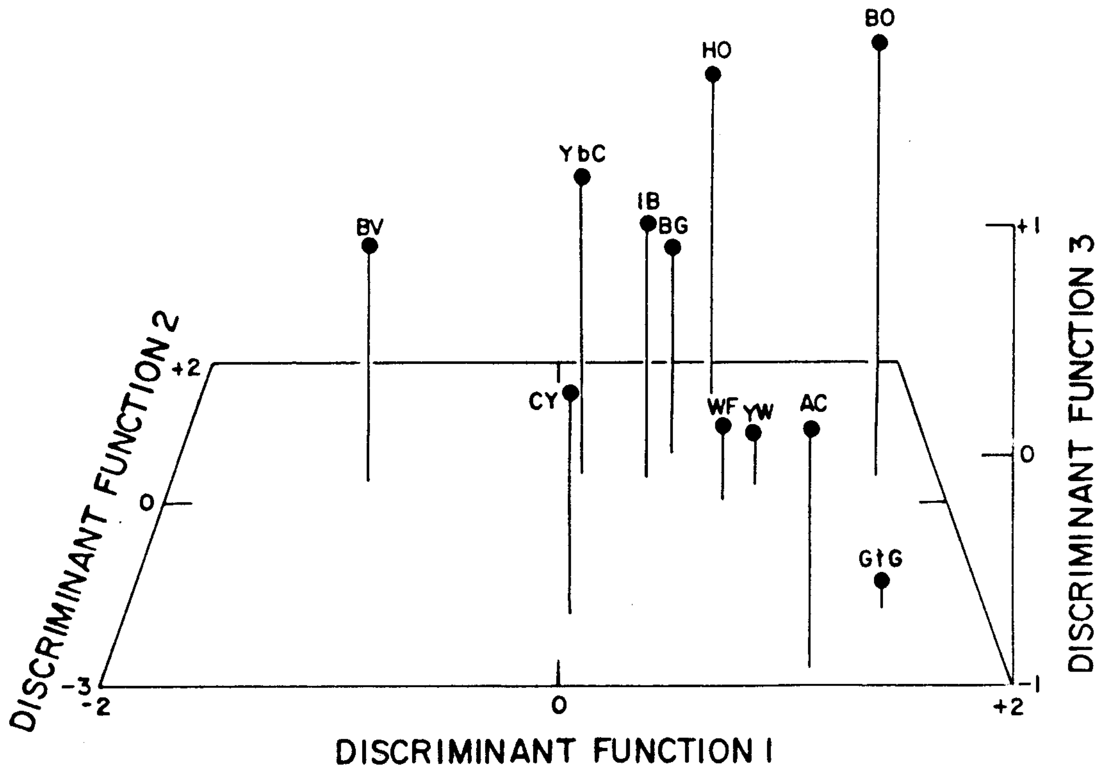

Figure 2. Location of the relative habitat preferences in three-dimensional "habitat space" of 11 species of breeding birds. Increasing values on the first function indicate a trend toward taller vegetation and habitat patchiness. Decreasing values on the second function indicate marshy or dense, low vegetation. The third function separates species based on a complex interaction between ten habitat variables. Species codes are: AC=American coot, WF=willow flycatcher, BV=Bell's vireo, YW=yellow warbler, YbC=yellow-breasted chat, CY=common yellowthroat, IB=indigo bunting, BG=blue grosbeak, HO=hooded oriole, BO=northern (Bullock's) oriole, and GtG=great-tailed grackle.

chosen by each species within the "habitat space" of the statistical model. Bell's vireo and American coot selected nesting habitats that were the most dissimilar; yellow warbler and willow flycatcher chose nesting habitats that were the most similar. Bell's vireo, willow flycatcher, and yellow warbler were the most extreme generalists in habitat choice in the river corridor, while American coot, blue grosbeak, and northern (Bullock's) oriole were the most specialized. The abundance of all five indicator species of birds has increased since 1976 (Table 2). A decline in numbers after the 1983 surplus water release was observed in Bell's vireo, yellow warbler, and common yellowthroat populations. The declines can largely be attributed to the effects of the 1983 surplus water release, specifically nest inundation combined with habitat loss through streambank erosion. These species had all recovered to or surpassed their pre-1983 densities by 1986, with the exception of common yellowthroat (for which pre-1983 density information was partly lacking). The recovery times exhibited by these indicator species denoted a breeding bird recovery cycle of approximately two to three years in response to the effects of the 1983 surplus water release.

Table 2. Yearly index to the population densities of five indicator species of obligate riparian birds between Lees Ferry and Diamond Creek along the Colorado River in Grand Canyon, 1976 to 1986.

	Number of Singing Males Heard					
Species	1976	1982	1983	1984	1985	1986
Willow flycatcher*	1+	2	4	4	8	11
Bell's vireo**	67++	135	78+++	92	75	121
Yellow warbler***	17+	32	39	33	61	80
Common yellowthroat***	8+	-	-	21	21	29
Yellow-breasted chat*	18+	46	53	65	62	101

* Census data from June of each year.

** Census data from mid-April to early May of each year.

*** Census data from late May to June of each year.

\+ From Carothers and Sharber (1976). Average absolute density for April, May, and June, 1974-1976.

++ From the April 1976 field journal of S.W. Carothers (Brown et al. 1983).

+++ Census inaccurate due to poor weather and high winds.

CONCLUSIONS AND RECOMMENDATIONS

The extent and timing of surplus water releases above 31,000 cfs during the breeding season have the potential to inundate a substantial number of the nests of certain birds. Management attention should be focused on the fact that breeding for most species along the river peaks from May to July, indicating that surplus releases should be avoided at that time. Many birds will renest if their initial nesting attempt is unsuccessful, but only if adequate time remains for the effort during their normal breeding period. The presence of very high water throughout most of the summer of 1983 prevented many birds from renesting, further reducing that season's nesting success.

If surplus releases during the breeding season cannot be avoided, then releases should be increased as soon as surplus water is predicted. These surplus releases should either remain constant or decrease slightly to allow birds to adjust to the higher water levels and renest.

Certain obligate riparian birds are especially sensitive to future management of fluctuating flows. These species include those habitat specialists that: (1) are restricted to the NHWZ, (2) are of rare or localized occurrence, or (3) nest closest to the water's edge or in marshy habitats. This management-sensitive group includes American coot, willow flycatcher (although it was identified as a generalist), common yellowthroat, and Bullock's oriole. Any future habitat change or loss would have a disproportionately large effect on these species.

The most serious long-term management consideration with respect to breeding birds is the potential for loss of riparian habitat through riverbank erosion. If fluctuating flows are causing such erosion, then the overall density and diversity of breeding birds will decline, particularly in the NHWZ, which presently exhibits the highest avian density. Conversely, if fluctuating flows can be shown to stabilize or increase the extent of river terraces supporting riparian vegetation, this would be of long-term benefit to birdlife.

Periodic flooding in the form of surplus water releases, even if it should cause short-term inundation of the nests of some species of birds, could be of long-term benefit to the overall breeding bird community if flooding maintained the dense, young stages of vegetation needed by some species. This periodic flooding would be useful only if riverbank erosion associated with flooding were not excessive.

Overall, fluctuating flows with restricted maximum releases (such as not exceeding 25,000 cfs) would be of the greatest long-term benefit to birds. Some changes in the birdlife of the river corridor will continue to occur regardless of how the dam is operated. However, management now has the capability to predict, direct, and even enhance this process of change in the breeding bird community.

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LIZARDS ALONG THE COLORADO RIVER IN GRAND CANYON NATIONAL PARK: POSSIBLE EFFECTS OF FLUCTUATING RIVER FLOWS

Distribution, abundance, and reproduction of selected lizard species were studied in riparian habitats along the Colorado River. Shoreline and nearshore riparian habitats were found to support the highest densities and the highest reproductive rates for most lizard species. High lizard density in shoreline habitats within one year of the 1983 flood suggests that lizard populations are very resilient to the deleterious effects of high river flow levels.

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INTRODUCTION

The contribution of riparian habitat to local species density and diversity of birds and mammals has been relatively well-studied. Gallery forests of cottonwood and willow along southwestern rivers have some of the highest densities of nesting birds in North America, much higher than in surrounding semiarid upland sites (Anderson, Higgins, and Ohmart 1977; Johnson et al. 1977). Riparian habitats contribute breeding sites, feeding areas, and migratory routes for birds. Mammal species diversity is also higher along watercourses, where some species find cover that is lacking in more open adjacent arid vegetation (Anderson, Drake, and Ohmart 1977), although small mammal densities in upland vegetation may be higher.

Reptiles, in contrast, have been little studied with respect to the importance of riparian habitats to their density and diversity. It is common to find comments in the literature about the higher density of some species in riparian sites (Lowe and Johnson 1977; Tinkle 1982; Vitt and Ohmart 1977), and researchers have performed some studies of lizard demography in riparian areas (Tinkle 1976; Tinkle and Dunham 1983; Vitt and Van Loben Sels 1976). However, quantitative studies comparing reptile density and diversity in riparian and adjacent non-riparian habitats are few. Studies on riparian ecosystems have only recently begun to address effects of management practices and habitat manipulation on riparian reptile communities (Jakle and Gatz 1985; Jones and Glinski 1985; Szaro et al. 1985).

In this study we examined the distribution of reptilian species relative to riparian habitats along the Colorado River in Grand Canyon National Park. The work was part of a larger study to determine the effects of fluctuating and flood releases from Glen Canyon Dam on plant and animal populations in and along the Colorado River. We gathered our data during constant flow levels of approximately 40,000 cubic feet per second (cfs) in June 1984, 25,000 cfs in August 1984, 35,000 cfs in June 1985, and 25,000 cfs in August 1986.

OBJECTIVES

The goal of this project was to evaluate the effects of fluctuating river levels, as controlled by Glen Canyon Dam, on the herpetofauna of the Grand Canyon. Because no information previously existed about the distribution and population ecology of the herpetofauna in Grand Canyon, the primary focus of the study was to analyze patterns of habitat use by reptile and amphibian species and to determine the relative importance of riparian habitats to the density and diversity of those populations. Our analysis emphasized those lizard species for which we had the largest sample sizes: those species that were most readily censused within the project's time and manpower constraints. Interpretation of possible effects of fluctuating river flow levels on the herpetofauna of the riparian corridor was a secondary emphasis based on indirect inferences since no fluctuating flows occurred during the study period.

METHODS

STUDY AREA. We censused sites along the Colorado River in Grand Canyon National Park beginning near Lees Ferry and extending downstream 220 miles almost to Diamond Creek. The elevation at river level dropped from approximately 945 m (3,100 ft) at Lees Ferry (River Mile [RM] 0) to approximately 427 m (1,400 ft) at the last census locality at RM 220. The upland vegetation along the river is generally Mohave desertscrub. There is, however, a gradual transition from more cold-tolerant species at the upper end of the study area to many frost-sensitive species at the lower end (Warren et al. 1982).

Two vegetation zones, more or less distinct in species composition and distribution, characterize the riparian corridor. Prior to construction of Glen Canyon Dam in

1963, floods scoured the river channel on a regular basis. The only riparian vegetation formed a belt along the high water line where flood disturbance was minimal. Since dam construction, lack of large-volume flooding has allowed plants, many of them exotic, to grow along the water's edge (Turner and Karpiscak 1980). The original riparian vegetation (called here the Old High Water Zone, or OHWZ), consisting largely of mesquite (Prosopis glandulosa) and catclaw acacia (Acacia greggii), is now perched on talus slopes and alluvial terraces several meters above the current average water level. The new riparian vegetation (called here the New High Water Zone, or NHWZ) dominated by tamarisk (Tamarix chinensis) and arrow-weed (Tessaria sericea), occupies sand and cobble bars along the water's edge.

SAMPLING PROCEDURES. We used visual belt transects, modified from the Emlen (1971) bird census technique, to census the common diurnal species (Lowe and Johnson 1977). This method involved walking transects through representative areas of the target habitats and recording all individuals observed within a 4 m-wide belt. Transect length varied with size of the habitat patch, but was usually 100 to 300 m. We selected transect sites to sample variation within old and new riparian habitats and in adjacent non-riparian desertscrub. Transects were visually selected to sample homogenous stands of each habitat. We recorded the time of day at the beginning and end of each transect walk, as well as a temperature profile consisting of soil surface temperature and air temperature at 5 mm and 1.5 m above the soil surface. We also noted wind speed and other weather conditions such as cloudiness.

As each individual lizard was sighted, we recorded distance along the transect and substrate upon which it was first observed, as well as its sex and age, when possible. Substrate categories used were bare soil, litter, rock (less than 1 m in diameter), boulder (greater than 1 m in diameter), cliff face, or tree. When individuals were in a tree, we recorded tree species and height above ground.

HABITATS SAMPLED. We sampled ten habitats distributed in four zones relative to the river. The first zone was shoreline habitats within 5 m of the river shore. The second zone was NHWZ riparian vegetation greater than 5 m from the river shore. The third zone was OHWZ riparian vegetation, which always occurred at a greater distance from the shore than the NHWZ vegetation. The fourth zone was non-river habitats, both upland desertscrub and tributary riparian (Table 1).

Table 1. Location of study sites for lizard transect sampling in 1984. Number of habitats sampled in each vegetation zone is indicated for each site. Under River Mile, R and L mean right and left shore when facing downstream.

Site Name	River Mile	Shore-line	River Riparian	Non-River
Lees Ferry	-1R		1	1
Badger	8R	1		
none	16L	1		
none	20R	1		
North Canyon	20.5R	1		
none	43.5L	1		
Saddle Canyon	47R	1	3	1
Nankoweap	53R	2	3	2
Kwagunt	56R	1		
Cardenas	71L	1	4	
Cremation	86L		1	
none	94L		1	
Crystal	98R	1		
Bass	108.5R	1	2	1
Elves Chasm	116.5L	1	1	
Forster	123L		2	
Tapeats	134R	1		1
none	140L	1	1	
Kanab	143.5R	1	4	
National	166L	2	1	
Stairway	171R	1	2	
none	185R	1	3	1
Whitmore	188R		3	
Parashant	198R	1	3	1
Granite Park	209L	1	1	
Three Springs	216L	1		
220 Mi. Canyon	220R	1		
Total Transects		24	36	8
Total Transect Length (meters)		2,665	5,522	2,420

We sampled three distinct habitats in the river shoreline zone: cobble shore, rocky shore, and vertical rock faces at the water's edge. All of these habitats had low vegetation cover, usually less than 10 percent. Cobble shores generally had numerous rocks less than 0.5 m in diameter and rounded by erosion. Larger, uneroded boulders were absent and large patches of bare sand were occasionally present. Cobble shores generally occurred at the mouths of tributary canyons, where coarse alluvium was washed into the river, forming level cobble bars.

In contrast, rocky shores consisted of rock fragments varying from cobbles to boulders several meters in diameter. These shores were generally uneroded talus and rockfall debris with occasional pockets of bare sand trapped among the boulders. In contrast to the level cobble shores, rocky shores usually fell steeply to the water's edge and were commonly very rugged and irregular.

Sandy shores and heavily vegetated shores were examined, but not sampled systematically for several reasons. Dense vegetation immediately at the water's edge was uncommon. In most locations where dense cover was present near the shore, it occurred on sandy soil. Frequently, erosion of sandy soil along the river's edge kept the immediate shoreline free of dense cover even though adjacent sandy bars were thickly vegetated. Open sandy shorelines that lacked vegetation or rock cover had no reptiles and amphibians. Although such sandy shores were spot-checked repeatedly, no systematic transects were sampled.

Within the riparian NHWZ, we sampled three post-dam habitats: open tamarisk with 15-40 percent cover, dense tamarisk with 60-100 percent cover, and arrowweed with cover similar to the open tamarisk. Open tamarisk and arrowweed habitat categories were similar in structure and intergraded extensively in species composition. For that reason, they were combined for some analyses in the later part of the study. We sampled two pre-dam habitats in the OHWZ riparian vegetation: mesquite/acacia alluvial terraces and mesquite/acacia talus slopes. Finally, we sampled two habitats in the non-river zone: desertscrub on canyon slopes generally ranging from a 15-30 percent grade, with 15-30 percent vegetation cover, and non-river riparian habitats along perennial tributary streams.

We assessed habitats in September 1983 and April 1984, then performed the census during June and August 1984.

At that time, we sampled between one and five habitats per locality (Table 1) with a total of 68 transects at 27 localities. Censuses were repeated in June 1985 and in May, June, and August 1986. A total of 79 transects were sampled during each of those years.

RESULTS AND DISCUSSION

We recorded five common diurnal lizard species using the belt transect method. One lizard species (Holbrookia maculata), two toad species (Bufo punctatus and B. woodhousei), and one frog species (Hyla arenicolor), occurred in numbers too small for adequate conclusions to be drawn concerning distribution patterns. Eight snake species were observed during the course of the study. Rattlesnakes were by far the most abundant, with 11 observations of Crotalus viridis abyssus and 9 of C. mitchellii. Of the remaining snakes, Masticophis taeniatus was third most common with five sightings, and M. flagellum, Lampropeltis getulus, Pituophis melanoleucus, Sonora semiannulata, and Diadophis punctatus were observed only once or twice each. Although there was a weak trend toward more frequent snake sightings in riparian habitats, the pattern was not significant due to an insufficient sample.

SUBSTRATE PREFERENCE. Lizards showed strong species-specific patterns of substrate preference (Table 2). No two common species occurred with highest frequency on the same substrate, although up to four species were commonly observed along a single transect.

Side-blotched lizards (Uta stansburiana) were the most common species (Table 2) as well as the smallest. They were found predominately in open sites, on rocks less than 1 m in diameter, or on bare soil. They were rarely more than 1 m away from the cover of rocks or small shrubs.

Western whiptail lizards (Cnemidophorus tigris), the second most abundant species (Table 2), were found most frequently on bare soil or litter. They often occurred in the same habitats with Uta, but unlike Uta, rarely perched on small rocks. Cnemidophorus was the only species commonly observed to roam up to several meters across open sand away from cover.

Desert spiny lizards (Sceloporus magister) were approximately equal in abundance to Cnemidophorus, although they were less noticeable due to more sedentary habits

Table 2. Distribution of lizards on substrates along the Colorado River in Grand Canyon, June and August 1984. Numbers in parentheses indicate percent of individuals of each species observed on each substrate.

Species	Substrate						Total
	Litter	Bare Soil	Rock <1m	Boulder	Cliff	Tree >1m	
<u>Uta stansburiana</u>	2 (1.3)	70 (46.7)	71 (47.3)	2 (1.3)	1 (0.7)	4 (2.7)	150
<u>Cnemidophorus tigris</u>	9 (9.5)	78 (82.1)	4 (4.2)	3 (3.2)	0	1 (1.1)	95
<u>Sceloporus magister</u>	11 (12.5)	11 (12.5)	7 (8.0)	34 (38.6)	3 (3.4)	22 (25.0)	88
<u>Urosaurus ornatus</u>	3 (4.9)	1 (1.6)	9 (14.7)	16 (26.2)	27 (44.3)	5 (8.2)	61
<u>Crotaphytus insularis</u>	0	1 (14.3)	4 (57.1)	2 (28.6)	0	0	7
<u>Sauromalus obesus</u>	0	0	0	1 (100)	0	0	1
<u>Holbrookia maculata</u>	0	1 (100)	0	0	0	0	1
Total	25	162	95	58	40	32	403

and a preference for cryptic vertical substrates such as large boulders and/or trees. Desert spiny lizards were most commonly on boulders larger than 1 m in diameter, usually with fractures and crevices. At sites without boulders but with trees (such as tamarisk stands on sandbars), this species also occurred on larger tree trunks. When they were observed on the ground, they were almost invariably at the base of a large tree or boulder.

Tree lizards (<u>Urosaurus ornatus</u>) also used vertical substrates; however, they preferred sheer, vertical rock faces on cliffs or large boulders. Cliff faces that dropped vertically into the river, usually along eddies or quiet stretches, had the highest densities of tree lizards. They often sat less than 1 m above water level, just above the splash zone, on faces with no fractures or other protection and that were up to 20-40 m from the nearest water-level alluvial soil.

We saw black collared lizards (Crotaphytus insularis) and chuckwallas (Sauromalus obesus) much less frequently than the four preceding species. These two species were also more common in desertscrub than in the riparian corridor. Collared lizards generally were observed perched on rocks or on small boulders approximately 1 m in diameter or slightly smaller. We rarely saw Chuckwallas on transects, but additional observations indicated that they preferred deeply fractured boulders and rock outcrops.

PATTERNS OF DENSITY AND HABITAT OCCUPATION. The most striking observation was the large differences in lizard densities among habitats (ANOVA with unequal sample size, $F=17.41$, Prob. <0.001; Tables 3a,b,c). Total lizard densities were highest in shoreline and open New High Water Zone riparian habitats and lowest in desertscrub, with intermediate densities in Old High Water Zone sites. Most species followed the general pattern, with highest densities in shoreline and NHWZ habitats and lowest density in desertscrub. The only exception was the collared lizard, which, although relatively rare, was seen more commonly in desertscrub than in any other habitat.

Direct comparison of density values derived from visual transects in this study with density data available in the literature is difficult for several reasons. First (and most important), our visual census did not account for every lizard in the study site as would a mark/recapture study on a permanent grid. Visual transect estimates will therefore generally be lower than a comparable mark/recapture estimate. Second, lizard densities vary substantially between sites, and between years, seasons, or even days at a single site. Thus, any comparison of densities, regardless of the sample technique, is fraught with problems unless the sampling is performed simultaneously at all sites compared. With these problems in mind, it is still useful to compare our results with density data available in the literature.

In general, lizard densities along the Colorado River were within the range of values observed for these species in other areas (Table 4). We found Urosaurus ornatus to occur in the highest density, as was true in several other studies. Similarly, of the four most

Table 3a. Lizard densities in habitats along the Colorado River in Grand Canyon, Arizona during June and August 1984. Values are mean number of individuals per hectare.

Habitat	Month	Lizard Species					All Lizards
		Uta	Cnemidophorus	Scelop-orus	Urosaurus	Crotaphytus	
Shoreline (<5m)							
Rocky Shore	June	48	23	60	20	0	150
	Aug.	20	0	0	100	0	120
Cobble Bar	June	68	40	15	0	3	125
	Aug.	60	18	13	0	0	90
Cliff Face	June	0	0	0	858	0	858
	Aug.	0	0	0	223	0	223
River Riparian (>5m)							
(NHWZ)							
Open Tamarisk	June	31	101	59	14	0	206
	Aug.	53	60	60	0	0	173
Arrowweed	June	35	35	5	0	0	73
	Aug.	33	18	18	0	0	68
Dense Tamarisk	June	0	13	40	0	0	53
	Aug.	no sample					
(OHWZ)							
Terrace	June	30	15	15	3	1	65
	Aug.	0	0	13	25	0	38
Talus	June	28	10	15	0	0	53
	Aug.	no sample					
Non-River							
Desertscrub	June	18	8	5	0	2	30
	Aug.	5	5	0	0	5	15
Riparian	June	25	0	125	150	0	300
	Aug.	208	0	0	0	0	208
Grand Mean (All habitats)	June	35	25	23	10	0.7	93
	Aug.	30	13	13	23	1	80

Table 3b. Lizard densities in habitats along the Colorado River in Grand Canyon, Arizona during June 1985. Values are mean number of individuals per hectare.

Habitat	Lizard Species					All Lizards
	Uta	Cnemidophorus	Sceloporus	Urosaurus	Crotaphytus	
Shoreline (<5m)						
Rocky Shore	94	17	53	37	1	202
Cobble Bar	69	10	14	33	0	126
Cliff Face	0	0	200	350	0	550
River Riparian (>5m)						
(NHWZ)						
Open Tamarisk	36	23	27	0	0	86
Arrowweed	39	78	7	0	0	123
Dense Tamarisk	0	41	30	0	0	71
(OHWZ)						
Terrace	22	9	14	0	0	45
Talus	9	0	10	0	0	19
Non-River						
Desertscrub	23	4	3	0	1	31
Grand Mean (All habitats)	43	13	20	14	0.4	90

Table 3c. Lizard densities in habitats along the Colorado River in Grand Canyon, Arizona during 1986. Values are mean number of individuals per hectare.

Habitat	Lizard Species					All Lizards
	Uta	Cnemi-dophorus	Scelop-orus	Uro-saurus	Crota-phytus	
Shoreline (<5m)						
Rocky Shore	124	17	29	32	0	202
Cobble Bar	92	13	25	42	0	172
River Riparian (>5m)						
(NHWZ)						
Open Tamarisk	18	73	50	0	0	141
Arrowweed	50	75	12	0	0	137
Dense Tamarisk	0	42	69	14	0	125
(OHWZ)						
Terrace	28	4	3	0	0	35
Talus	9	0	10	0	0	19
Non-River						
Desertscrub	12	2	00	0	1	15
Grand Mean (All habitats)	43	14	14	11	0.3	82

Table 4. Comparison of average lizard densities in Grand Canyon with those from other localities. Ranges are shown in parentheses. In some cases the ranges are from replicate sampling in adjacent sites, and in some cases from sampling in different years.

Species	Average Density (Number/ha)	Location	Source
Uta	140 (62-238)	Texas	Tinkle 1967
stansburiana	22	Ariz. desertscrub	Vitt and Van Loben Sels 1976
	7	Ariz. mesquite	Vitt and Van Loben Sels 1976
	7	Ariz. riparian	Vitt and Van Loben Sels 1976
	33 (0-208)	All habitats	This study
Cnemidophorus	12 (8-18)	Nevada	Turner et al. 1969
tigris	8 (3-15)	Texas	Degenhardt 1966
	17	Colorado	McCoy 1965
	30	Nevada	Tanner and Jorgensen 1963
	114 (45-184)	Texas	Milstead 1967
	3	Ariz. grassland	Lowe and Johnson 1977
	12	Ariz. desertscrub	Vitt and Van Loben Sels 1976
	32	Ariz. mesquite	Vitt and Van Loben Sels 1976
	32	Ariz. riparian	Vitt and Van Loben Sels 1976
	7	Ariz. dry wash	Vitt and Van Loben Sels 1976
	19 (0-78)	All habitats	This study
Sceloporus	15	Utah riparian	Tinkle 1976
magister	10	Ariz. desertscrub	Vitt and Van Loben Sels 1976
	25	Ariz. mesquite	Vitt and Van Loben Sels 1976
	25	Ariz. riparian	Vitt and Van Loben Sels 1976
	18 (0-125)	All habitats	This study
Urosaurus	158 (131-188)	Ariz., spring	Tinkle and Dunham 1983
ornatus	101 (42-161)	Ariz., summer	Tinkle and Dunham 1983
	370	Ariz. mesquite	Vitt and Van Loben Sels 1976
	185	Ariz. riparian	Vitt and Van Loben Sels 1976
	16 (0-858)	All habitats	This study
Total	6 (2-12)	Southwest deserts	Pianka 1967
Lizards	55	Ariz. riparian	Lowe and Johnson 1977
	66	Ariz. grassland	Lowe and Johnson 1977
	8	Ariz. Chihuahuan Desert	Lowe and Johnson 1977
	593	Ariz. mesquite	Vitt and Van Loben Sels 1976
	277	Ariz. riparian	Vitt and Van Loben Sels 1976
	89	Ariz. Sonoran Desert	Vitt and Van Loben Sels 1976
	12	Ariz. dry wash	Vitt and Van Loben Sels 1976
	86 (15-858)	All habitats	This study

common species, Sceloporus magister, had the lowest density. Sceloporus was reported by several other authors to have lower densities as well. These results indicate that visual transect data are roughly comparable with mark/recapture data.

The average June densities of 858 lizards/ha on shoreline cliff faces, and 300 lizards/ha in non-river riparian habitats, equal or exceed lizard densities reported in the literature for any habitat. This observation is of particular interest considering the expected under-estimate of a visual census compared to mark/recapture methods. The lizard densities we observed in riparian habitats along the Colorado River were higher than those in most habitats thus far studied in the Southwest. They were up to an order of magnitude higher than densities we observed in desertscrub immediately adjacent to the river corridor.

The most likely explanation for these high densities is an increased abundance of food resources. Many shoreline sites appear to have much greater numbers of insects than non-riparian areas for two major reasons. First, debris washed up along the water's edge in eddies and backwaters is frequented by many insects. Second, many riparian plant species support a larger insect fauna than non-riparian species (Stevens 1976). The two highest local lizard densities observed anywhere along the river were both at sites along the shoreline where lizards were feeding upon insects. The highest density was observed at Cardenas where a total of eight Cnemidophorus tigris and five Sceloporus magister were observed feeding along the shoreline in an area of approximately 3 x 7 m, or a density equivalent to 6,500 lizards/ha. In spite of their close proximity to one another, no antagonistic interactions were observed between individuals of either species, and all were active in the area for an hour. The second highest density was observed on a vertical rock face at the waterline on which eight Urosaurus ornatus were observed in an area of 2 x 25 m, or 1,600/ha. Again, they were feeding on insects at the water's edge with no apparent antagonistic interactions for an extended period of time.

The distributions of several of the lizard species studied were consistent with the concept of "preferential" riparian species as used by Johnson et al. (1984) in their discussion of plant species distributions. Urosaurus, Cnemidophorus, Sceloporus, and Uta could be considered "preferential" riparian species by virtue of their higher densities in riparian habitats compared to non-riparian. As with the original application of these terms to plant distributions, it is important to note that these classifications refer only to local distribution and do not apply throughout the species' ranges.

The pattern of differences in lizard densities among habitats was stable through time as shown by comparison of data from different seasons and different years (Table 5). Correlation analysis of density data gathered in the same habitats during consecutive years indicates that differences in total lizard densities between habitats were stable year to year (1984/1985 r=0.94, n=12; 1985/1986 r=0.93, n=11).

Table 5. Variation in lizard densities in riparian and non-riparian habitats along the Colorado River between 1984 and 1986. Mean densities are individuals/ ha. Sample size indicates number of transects sampled in each habitat.

Habitat	1984			1985			1986		
	mean	S.D.	n	mean	S.D.	n	mean	S.D.	n
<u>Shoreline</u>									
All sites	425	1,067	26	179	143	36	186	98	21
Rock face	782	840	4	550	--	1	--	--	--
Rocky shore	144	82	11	199	119	17	203	118	10
Cobble bar	98	68	11	125	136	18	167	69	11
<u>NHWZ</u>									
All sites	94	74	16	91	77	15	125	82	9
Open Tamarisk	184	142	7	87	82	6	141	94	5
Arrowweed	96	77	5	124	75	4	137	124	2
Dense Tamarisk	72	75	4	71	92	5	125	119	2
<u>OHWZ</u>									
All sites	56	49	18	37	34	16	29	28	11
Talus	56	49	7	19	29	8	<8	--	2
Terrace	55	51	11	46	38	8	36	27	9
<u>Non-riparian</u>									
Desertscrub	21	22	6	32	21	12	15	11	7

Comparison of densities observed during the two different census periods in 1984 shows a decline from June to August (Table 2). It appears that the cooler, cloudier weather encountered during the August census resulted in lower activity levels of some species. Whiptails and desert spiny lizards both declined in observed densities by approximately one-half between the two census periods.

POPULATION RESILIENCE TO FLUCTUATING FLOWS. The observation that 1984 lizard densities were highest in the shoreline zone, and that those densities were among the highest ever observed in lizard populations in the arid Southwest, suggests that lizard densities recovered to a large degree within one season from whatever deleterious effects they experienced due to the high water of 1983. The unusually high water of that year undoubtedly eliminated the populations on many cobble bars and lower rocky shores.

In some parts of the canyon, horizontal displacement of the shoreline from normal flow levels to high water levels during 1983 was up to 100 m across wide cobble bars. Vertical displacement between normal and high shoreline locations was up to 8 m. The observation that densities on shoreline sites were back to near maximum levels within one season after the flood, and before newly hatched young could disperse, suggests that many adult lizards recolonized the previously flooded shoreline as the water level dropped.

A weak trend was seen in shoreline and NHWZ riparian habitats toward a continued increase in lizard densities from 1984 to 1986 (Table 5). Most habitats showed a consistent, but non-significant, increase during the three years of observation, suggesting that populations near the river are not yet completely stable following the 1983 flood. The one major exception to the pattern of increasing densities in the riparian zone during 1984 to 1986 was Urosaurus. Inadequate sampling of cliff faces, their preferred habitat, during 1985 and 1986 resulted in an erroneous appearance of a large decline in Urosaurus numbers. It is important to note that the opposite trend in density was seen in OHWZ habitats, with a consistent decline in density between 1984 and 1986. One possible, but unsubstantiated, interpretation of this pattern is that some individuals are migrating from the higher old zone back into the new zone habitats that were left vacant by the high water of 1983. No consistent pattern of change in density between years was observed in the desertscrub.

REPRODUCTION. Reproductive activity of lizards along the Colorado River was not evaluated directly, but indirect evidence of reproduction was inferred from the distribution of immature individuals (Table 6).

Table 6. Relative densities of juvenile lizards in riparian habitats along the Colorado River expressed as percent of adult density. For the relative juvenile densities of all species chi-square = 40.75; $p < 0.001$. The "open shrub" habitat category combines open tamarisk and arrowweed.

Habitat	Uta	Sceloporus	Cnemidophorus	Urosaurus	Crotaphytus	All Species
Shoreline						
Cobble bar	30.2	175.0	16.7	13.8	--	29.6
Rocky shore	8.9	25.8	5.6	13.0	--	12.6
Rock face	0	31.8	0	5.3	--	9.1
NHWZ						
Open shrub	30.6	20.0	13.7	0	--	20.2
Dense tamarisk	33.3	0	0	0	--	1.4
OHWZ						
Terrace	12.0	16.7	0	0	--	10.0
Talus slope	0	0	0	0	--	0
Non-riparian						
Desert scrub	0	0	0	0	20.0	4.4

The greatest number of immature lizards was observed in shoreline and riparian habitats with a mosaic of bare sand, which provides nest locations, and cover such as cobbles and small shrubs. Uta juveniles were the most common and were often seen on cobble bars and the shoreline. Tinkle's (1967) observations that the average first-year dispersal of juvenile Uta is less than 6 m suggests that these habitats are the location of higher reproductive activity than non-riparian sites. Although the young of other species are likely capable of dispersing greater distances than do Uta, they are probably found within a few tens of meters of their hatching site during the first two or three months.

One unexpected observation was that juveniles of most species were generally found in highest proportions in a habitat other than that in which the adults achieved maximum density (Chi-square = 40.8, D.F.=7, Prob. <0.001). This was particularly apparent for Sceloporus magister, in which juveniles outnumbered adults by almost two to one on cobble bars. In the case of Urosaurus, this pattern is easily explained by the fact that the preferred adult foraging areas are rock faces that lack nest sites.

CONCLUSIONS

Shoreline lizard densities along the Colorado River were found to be higher than densities in riverine riparian vegetation, which in turn were higher than densities in non-riparian desertscrub. Shoreline densities for the most common species, which are among the most common and widespread lizard species in the Southwest, were higher than any previously reported anywhere else in the Southwest. The reason for the high densities observed is probably abundant food availability on riparian plants and among debris along the water's edge.

It is possible that rapidly fluctuating river flow levels have short-term deleterious effects on shoreline lizard populations for two reasons. First, rapidly rising water could trap and destroy large numbers of individuals on alluvial bars, and second, rising water during the breeding season from May to July may inundate nest sites in shoreline and riparian-zone sand. However, lizard populations appear to be very resilient to disturbance due to high river flow levels and reestablish rapidly along the shoreline.

RECOMMENDATIONS FOR OPERATING CRITERIA

The characteristics of river flow levels that are likely to adversely affect lizard, and other reptile and amphibian, populations are seasonality and rates of fluctuation, rather than absolute magnitudes of fluctuation. The critical season for these lizard populations is late spring and summer when reproduction occurs. Egg laying occurs primarily from April through June (Tomko 1976), followed by hatching and dispersal from June through August. During this period of time, rising water levels would inundate and destroy nests, which appear to be most abundant in shoreline and NHWZ habitats. Additionally, rapid changes in water levels (more than three to four vertical feet in less than one day) would be more likely to trap and destroy populations on cobble bars and beaches than gradual flow changes.

Based on these considerations, an ideal flow scenario for riparian herpetofauna would be a maximum annual river flow during late March or April, which would cause nest site selection to occur high on the shore, followed by a gradual reduction in flow through the summer without large, rapid fluctuations.

ACKNOWLEDGMENTS

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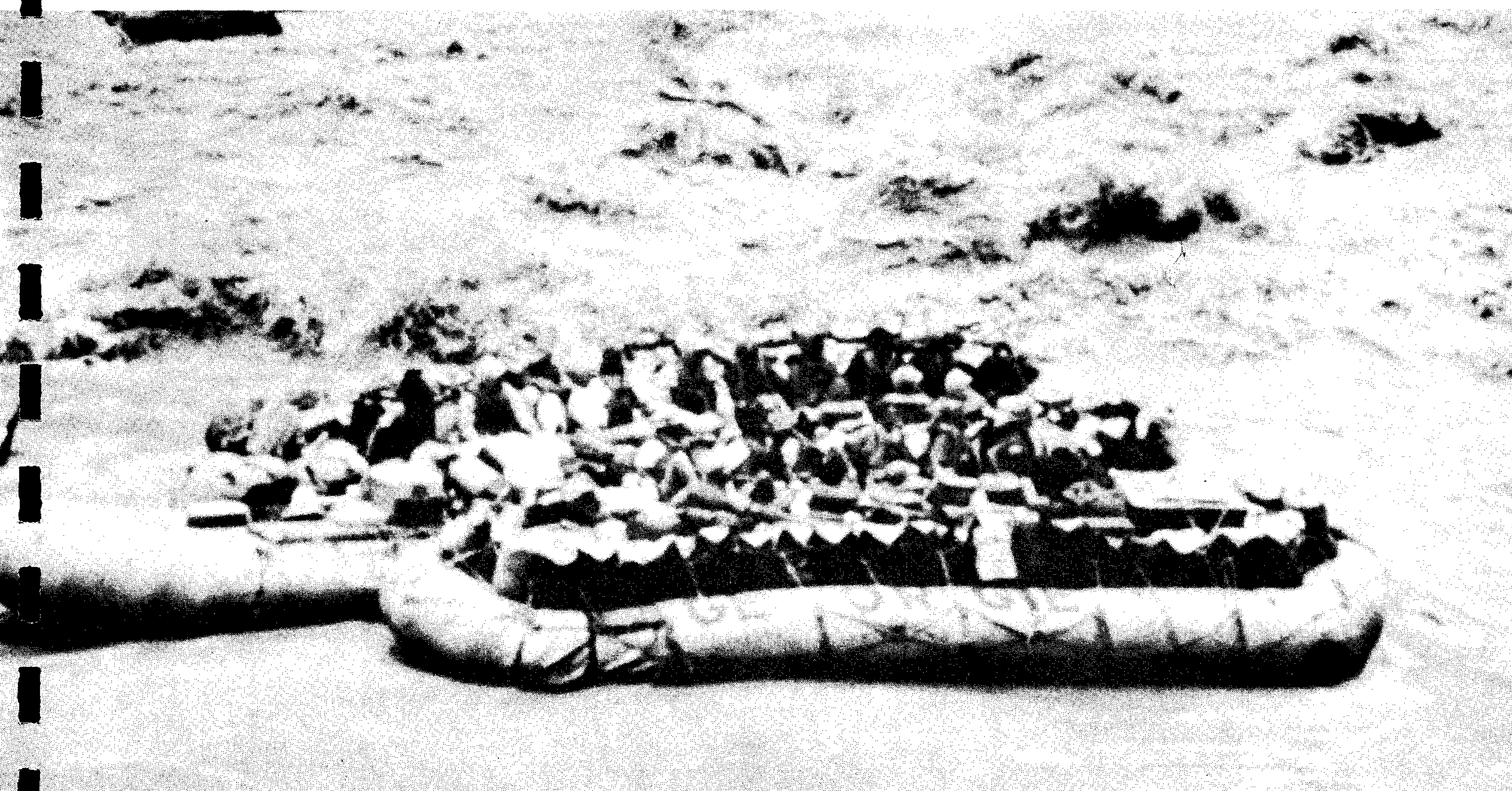
Section V: Recreation Reports



SECTION V: RECREATION REPORTS

GLEN CANYON DAM RELEASES AND DOWNSTREAM RECREATION: AN ANALYSIS OF USER PREFERENCES AND ECONOMIC VALUES

This study assesses the impact of Glen Canyon Dam releases on river runners and anglers in Glen Canyon National Recreation Area and Grand Canyon National Park, Arizona, using attribute and contingent valuation surveys.

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INTRODUCTION

Releases from Glen Canyon Dam into the Colorado River can vary from as low as 1,000 cubic feet per second (cfs) to 48,500 cfs and more, depending on hydrologic conditions, legal requirements, and management decisions. Furthermore, if the Glen Canyon Powerplant were operated to produce maximum on-peak power, releases could vary from as low as 1,000 cfs to as high as 33,500 cfs during each 24-hour period. This research focused on how Glen Canyon Dam releases affect the downstream recreational environment.

Three groups of recreationists that may be affected by flows were identified at the outset. The first is white-water boaters. This group is composed of people using rafts, dories, and other boats to travel downriver through Grand Canyon National Park. These may be either commercial trips provided by rafting companies for a fee or trips organized and conducted by private citizens. The second group of recreationists consists of boat and bank anglers who fish for trout in Glen Canyon National Recreation Area between Lees Ferry and Glen Canyon Dam. The third group of recreationists is composed of day-use rafters who utilize Glen Canyon between Lees Ferry and the dam. Day-use raft trips are provided commercially and involve a day of sightseeing and related activities along the river.

METHODS

Several sources of information and data were utilized in this study. Knowledgeable fishing guides, rafting guides, resource managers, and other Glen Canyon Environmental Studies (GCES) researchers provided valuable insights regarding recreation and the potential effects of flows.

In addition, seven formal surveys were conducted. One was a mail survey of white-water commercial trip guides and private trip leaders to ascertain their views on how dam releases affect white-water boating. Samples of white-water boaters, anglers, and day-use rafters each participated in "attribute surveys." These surveys were designed to identify the important attributes of recreational quality and define which are sensitive to flows. Participants in the attribute surveys were also queried directly regarding their preferences for alternative flows.

Finally, samples from each of the three user groups participated in a contingent valuation (CV) survey to quantify, in dollars, the effects of dam releases on their particular recreational experiences. Actual trips were valued first. Then, both white-water boater and angler respondents valued various scenarios that described trips under different flow conditions. In a sense, a scenario is a group of interdependent attributes. For example, a white-water boating scenario could not contain both maximum availability of camping beaches and very large rapids because beaches are most available at low water, while most major rapids get larger at high water. Such a scenario would not be relevant for decision making because it would be technically infeasible. The scenarios in this study were devised to be technically feasible and to describe changes in important flow-sensitive attributes of each experience as identified in the attribute surveys. Values were arrived at using contingent valuation, a technique that involves asking recreationists, in surveys, the maximum values they would place on access to recreational opportunities if they had to pay more for access. The outcome of applying contingent valuation was a dollar value per trip for the actual trip and a dollar value for each of the alternative trip scenarios. These values were estimated for all three user groups.

The ultimate goal of the study was to assess the impact of alternative annual flow release patterns or "annual flow regimes" for Glen Canyon Dam on recreationists in the aggregate. This goal was achieved by modeling the relationships between flow levels and monetary values. Values per trip, based on the results of the contingent valuation surveys, gave estimates of how recreationists would value individual trips under actual conditions and under conditions described in the scenarios. The evaluation of specific flow patterns required combining the values of white-water boaters and anglers with the number of trips taken by each group in 1985 to produce an estimate of aggregate recreational benefits.

Day-use rafting was not included in the model as analysis of the attribute survey showed that flow levels did not affect day-use rafting values over the range of flows analyzed. A computer model was developed to calculate aggregate recreational benefits over the range of possible annual flow regimes.

The use of dollar values is the most innovative feature of the study--and the feature that is likely to be the most controversial. We feel justified in using the concept for the following reasons. First, this study applied widely accepted economic principles and procedures. For example, we have striven for consistency between our study and the U.S. Water Resources Council (1983) where contingent valuation is endorsed as an acceptable technique for evaluating recreational benefits. Second, a substantial body of research on contingent valuation indicates that contingent values for recreation are sufficiently accurate to be used in policy analysis. Third, dollar measures of recreationists' preferences have some distinct advantages over alternative measures. One alternative would have been to ask people directly about their preferences. Indeed, we did so in the attribute surveys. However, such measures are difficult to combine or compare across user groups. Dollars are a commonly understood measure that greatly facilitate aggregation and comparisons across user groups. Obviously, many factors other than dollars of benefits must be considered in the management of any public resource, but dollar measures like those estimated in this study provide a new dimension to the information that can be used in resource decision making.

RESULTS AND CONCLUSIONS

WHITE-WATER BOATING. Glen Canyon Dam releases have substantial impacts on white-water boating. The contingent valuation results for white-water boating at constant flows are pictured in Figure 1. The vertical axis shows dollar values per trip and the horizontal axis shows average daily flows. The higher "flow value curve" applies to commercial white-water trip passengers while the lower flow value curve applies to private white-water trip passengers. These curves indicate that the ideal flow for commercial trips is about

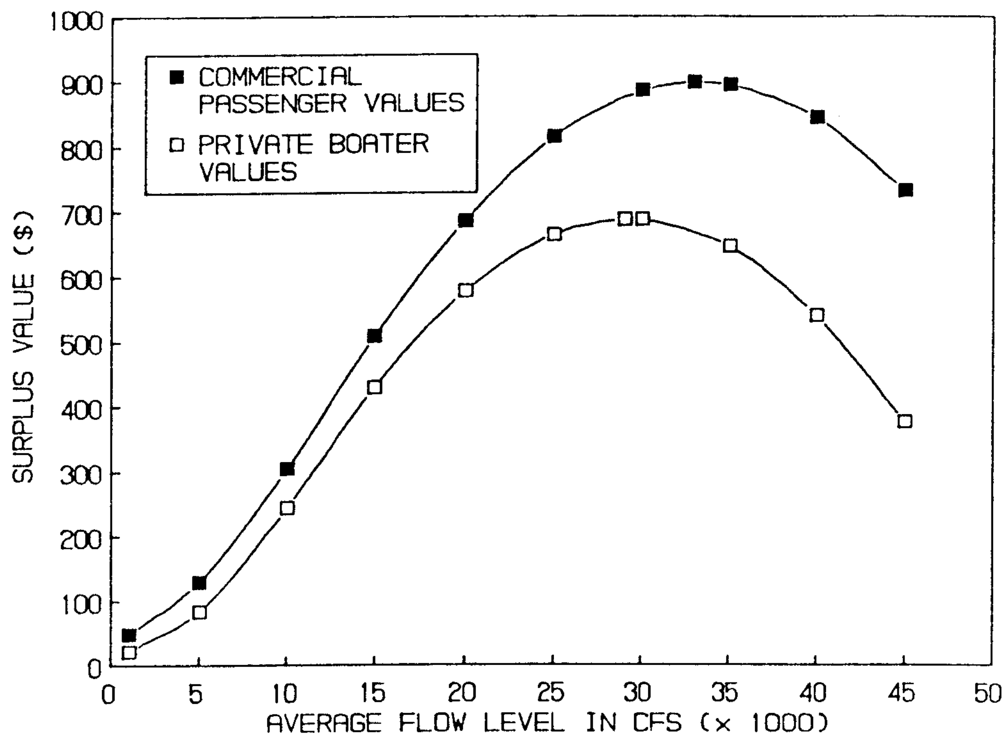

Figure 1. Relationship between surplus values and flow levels for respondents' actual trips ($ per trip).

33,000 cfs, while for private trips it is about 29,000 cfs. Above and below these ideal flows, values fall precipitously, indicating that white-water boating is sensitive to dam releases. Attribute and guide/private trip leader surveys indicate that higher and lower flows both reduce enjoyment of the famous Grand Canyon rapids and may create slightly less safe conditions. Higher flows can inundate sandbars used for camping and thus increase crowding in some reaches. Lower flows involve slower currents that can reduce time for attraction sites and for camping.

Except for low average daily flows (less than 10,000 cfs), fluctuating daily flows are detrimental to white-water boating compared to constant flows at the same average daily levels. The effects of fluctuations vary depending on the average daily flow and the particular boater, so precision is not possible. Nevertheless, it is possible to conclude, based on the attribute survey, that daily fluctuations become perceptible to most white-water boaters when they exceed roughly 10,000 cfs. Perceptible daily fluctuations are undesirable because they make the river seem less natural and make camping, boat mooring, and planning trip itineraries more complicated. Large daily fluctuations may reduce trip values by 20-30 percent or more.

Annual white-water boating benefits could be enhanced most by maintaining relatively high constant flows during the summer months. Based on 1985 use rates, about 67 percent all white-water boating trips (commercial and private trips combined) occur in June, July, and August, and 92 percent occur in the five months between May 1 and September 30. Thus, these are the months when dam operations are particularly important for white-water boating.

Very high flows (in excess of 40,000 cfs) will reduce white-water benefits, particularly during June, July, and August. Benefits per trip decline (Figure 1) beyond 35,000 cfs for both commercial and private trips.

Loss of large numbers of camping beaches would have a substantial adverse impact on white-water boating. Concerns have been voiced about the effects of dam releases on camping beaches. Our conclusion is conditional: if an erosional problem exists, it could have serious recreational impacts. Substantial reductions in camping beaches could reduce benefits per trip by one-third.

GLEN CANYON FISHING. Glen Canyon Dam releases have a substantial impact on the value of the fishing experience downstream. Figure 2 shows the flow value curves for anglers. The sharp appearance of these curves compared to those for white-water boating (Figure 1) reflects a difference in procedures. Figure 2 is based on respondents' evaluations of angling scenarios at flows of 3,000 cfs, 10,000 cfs, 25,000 cfs, and 40,000 cfs. Values for these flows are connected with straight lines, and extrapolations to 1,000 cfs and 45,000 cfs are included. The upper curve applies to constant flows while the lower curve applies to fluctuating flows. From the average angler's perspective, constant flows around 10,000 cfs are ideal. Lower and higher flows adversely affect perceived chances of catching fish and the ability of anglers to handle boats or to fish along the riverbanks.

Except at low flows, most anglers prefer constant flows to fluctuating flows. This result was clear from the angler attribute survey and also from the contingent valuation results. As can be seen in Figure 2, the fluctuating flow values lie below the constant flow

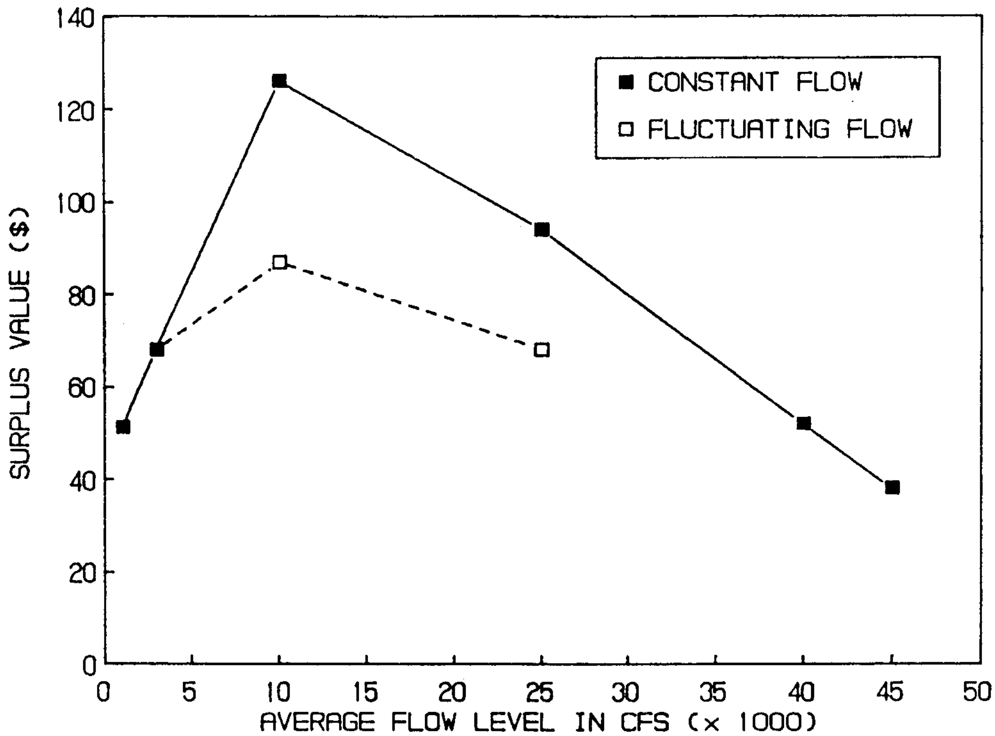

Figure 2. Glen Canyon angler flow value functions for constant and fluctuating flow levels ($ per trip).

values, except at 3,000 cfs. Fluctuating flows can reduce benefits per trip by as much as 30 percent.

Annual angling benefits could be enhanced most by maintaining moderate to low constant flows in the range of 10,000 cfs in the non-summer months. During 1985, for example, 86 percent of the angler trips to Glen Canyon occurred in the months from January through May and September through December. Thus, it is non-summer months when fishing benefits are most affected by dam operations.

In managing releases from Glen Canyon Dam, effects on the productivity of the downstream fishery could have large recreational impacts. This study focused on the ability of anglers to catch fish that are available at any given point in time. The long-term effects of flows on the biological productivity of the fishery are being studied by other GCES researchers. Conditional conclusions are nevertheless possible. If dam operations could help restore the trophy fishery that previously existed in Glen Canyon, annual benefits could easily double or more, based on increased participation and increased value per trip. If dam operations reduce biological productivity in the future, equally dramatic effects in the opposite direction will occur.

GLEN CANYON DAY-USE RAFTING. Glen Canyon Dam releases do not have significant impacts on day-use rafting over a very broad range of flows. Neither the attribute nor the contingent valuation surveys succeeded in identifying statistically significant effects of flows on this activity. Only if flow levels were totally unsuitable would day-use rafting be affected. For example, trips currently become unprofitable for the rafting company at flows above 46,000 cfs. In that case, benefits would be foregone in the amount of $26 per trip lost.

Recreational benefits could be compared to power benefits, if properly calculated, but not directly to power revenues. This is because power revenues are based to a considerable degree on the costs of the power and not its benefits. To correctly compare power revenues with recreational benefits would be a fairly complex and difficult project.

RECOMMENDATIONS

White-water boaters, both commercial and private trip passengers, prefer constant high flows during the summer months of June through August. Anglers prefer constant low to moderate flows. In terms of overall recreational benefits, white-water boaters dominate because they have a larger value per trip and a larger number of trips per year than anglers.

Flow regimes combining high constant flows in the summer months with moderate or low flows during the remainder of the year would be likely to produce the largest recreational benefits. Except for May and September, when both anglers and white-water boaters are quite active, the two activities have a strong tendency to occur at different times of the year. Even though anglers and white-water boaters prefer different flows, both groups could be accommodated to a considerable degree by running high summer flows in the vicinity of 30,000 cfs for white-water boating and low non-summer flows in the vicinity of 10,000 cfs for fishing. Compromises in May and September would be necessary. This scenario would depend on sufficient water to accommodate both groups. Given insufficient water, our analysis indicates that, from the perspective of increasing aggregate recreational benefits, white-water boating should be favored to a considerable extent. This is because the white-water boating population is large and has a high value per trip. An improved fishery, however, might reverse this conclusion.

In general, extreme high or low flow levels will adversely affect all river recreation. Flows below approximately 5,000 cfs and above 35,000 cfs are disagreeable to both boaters and anglers.

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EFFECT OF FLOWS IN THE COLORADO RIVER ON REPORTED AND OBSERVED BOATING ACCIDENTS IN GRAND CANYON

This study examines the relationship between river flow levels produced through operation of Glen Canyon Dam and the incidence of white-water boating accidents on the Colorado River in Grand Canyon.

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INTRODUCTION

Glen Canyon Dam is located on the Colorado River at Page, Arizona, near the Utah-Arizona state line. The dam, which forms Lake Powell, controls the flow of water in the river through Glen and Grand Canyons to Lake Mead. This study covers the Colorado River between Lees Ferry (15 miles downstream from the dam) and Diamond Creek, a distance of approximately 225 river miles, almost all of which is within Grand Canyon National Park.

To address the public concerns about the effect of dam operations on boating safety in the Grand Canyon, several accident studies have been conducted. Investigators have collected and analyzed several kinds of data addressing the relative hazard associated with running rapids at different flow levels and during fluctuating flows. Studies included surveys of white-water commercial guides, private trip leaders and passengers; discussions with boaters on the river; analysis of U.S. National Park Service (NPS) records of boating accidents; and an observation study of boats running rapids at different river flow levels. These several avenues of study converged on the conclusion that river flow levels are related to white-water boating accident rates in a statistically reliable fashion.

The Colorado River in the Grand Canyon presents an unusually severe hazard for white-water boaters due to the difficulty of the rapids and the danger for persons falling into the water. In addition to the high water velocities and turbulence, the very temperature of the water is life threatening. Water released from deep within Lake Powell at Glen Canyon Dam has a temperature of 42 degrees F and over its 225-mile journey through the canyon, warms only to 50 degrees F. Persons falling into the water have only a few minutes of useful activity before hypothermia prevents coordinated physical effort.

Since 1980, five persons have died while running the white-water in Grand Canyon: two at Lava Falls and three at Crystal Rapid. Two of the victims were in large, 30-ft motor rigs, one in a 16-ft oar raft, and one in a 16-ft paddle raft. All deaths resulted from falling into the water; in four of the cases after the boat had flipped in a rapid. Cause of death in four cases was drowning, in one case, heart failure. It is important to note that these deaths occurred after relatively brief periods of immersion, with victims wearing life vests in four of the five cases.

This record speaks to the serious hazard posed by the very cold and turbulent waters that rapidly exhaust, and can render unconscious, even the strongest swimmer. For this reason, falling out of a boat in Grand Canyon white-water, while usually only a chilling experience, carries the potential for serious harm.

At the same time, while white-water boating can be hazardous, it is the challenge and risk associated with large rapids that attract river runners, and define the essence of the white-water experience. Without the hazards and uncertainties associated with the white-water, much of its special appeal would be lost.

METHODS

Three surveys were used for this study: expert judgement, historical records, and direct observations.

(1) Expert judgement was obtained through a survey of 385 white-water guides in order to identify factors causing river accidents. The guides had an average of nine years experience in the Grand Canyon.

(2) Historical records were used to correlate incidence of reported white-water boating accidents with river flow levels for the years 1981, 1982, and 1983. These reports (NPS Case Incident Records) are filed whenever a medical evaluation is performed by NPS staff, evacuation of an injured person occurs, or an accident resulting in over $200 damage is reported.

(3) A direct observation study was conducted to provide a complete assessment of the relationships between river flows and the full range of accidents. Observers were placed in the Grand Canyon at ten rapids, at intervals between August 1985 and August 1986, covering periods of steady flows and fluctuating flows. Nearly 5,000 boats were observed. The observers recorded whether: (a) the boatman lost control of an oar, (b) the boat flipped, (c) the boat struck a rock, or (d) persons were lost overboard. They also recorded: (a) the length of time persons were in the water, (b) the most serious injuries, (c) equipment lost or damaged, (d) the number of persons who walked around the rapid, and (e) whether the boat was portaged or lined through the rapid.

RESULTS

GUIDE SURVEY. When asked to identify factors causing river accidents, the guides identified seven factors in the following order of importance: (1) boatman inexperience, (2) boatman error, (3) very low water (<5,000 cubic feet per second [cfs]), (4) very high water (>45,000 cfs), (5) equipment failure, (6) daily fluctuations, and (7) weather. Guides believe that very low and very high flows lead to accidents and specify approximately 8,000-9,000 cfs as the minimum, and approximately 45,000-55,000 cfs as the maximum safe flow levels, depending on the type of boat employed. Guides identified Horn Creek and Hance Rapids at low flows, and Crystal Rapid and Lava Falls at high flows as particularly difficult.

ACCIDENT RECORDS STUDY. The NPS Case Incident Records described 40 accidents during the three-year study period, covering 7,727 white-water trips. For these analyses, the range of river flows was broken into four categories: less than 9,999 cfs (Low), 10,000-16,999 cfs (Medium), 17,000-31,999 cfs (High), and greater than 32,000 cfs (Flood). The only significant relationship between accidents and flows occurred at Crystal Rapid, with motor rigs having more accidents at flood flows. The analysis of these accident records found no significant relationship between flow levels and reported accidents considering all rapids together. However, due to the very low frequency of accidents requiring evacuations (.052 percent), this is a relatively weak test of the relationship between flow levels and accident rates.

OBSERVATION STUDY. The data for Crystal Rapid covered the widest range of flow levels, and are used here to illustrate the observation study findings for the relationship between river flow level and accidents (Figure 1 and Table 1).

Table 1. Accident Rates at Crystal Rapid.

Type of Accident	Flow Category Low	Medium	High	Flood
Boat Struck Rock	.29	.07	.03	.01 *
Person in Water	.00	.01	.08	.08 *
Boat Flipped	.01	.02	.05	.08 *
Passengers Walked	.03	.22	.20	.45 *
Equipment Damage	.02	.02	.03	.03
Boat Lined or Portaged	.02	.07	.06	.18 *
Injury	.003	.004	.004	.006 *

* indicates that accident variable is significantly related to flow category at $p < .05$.

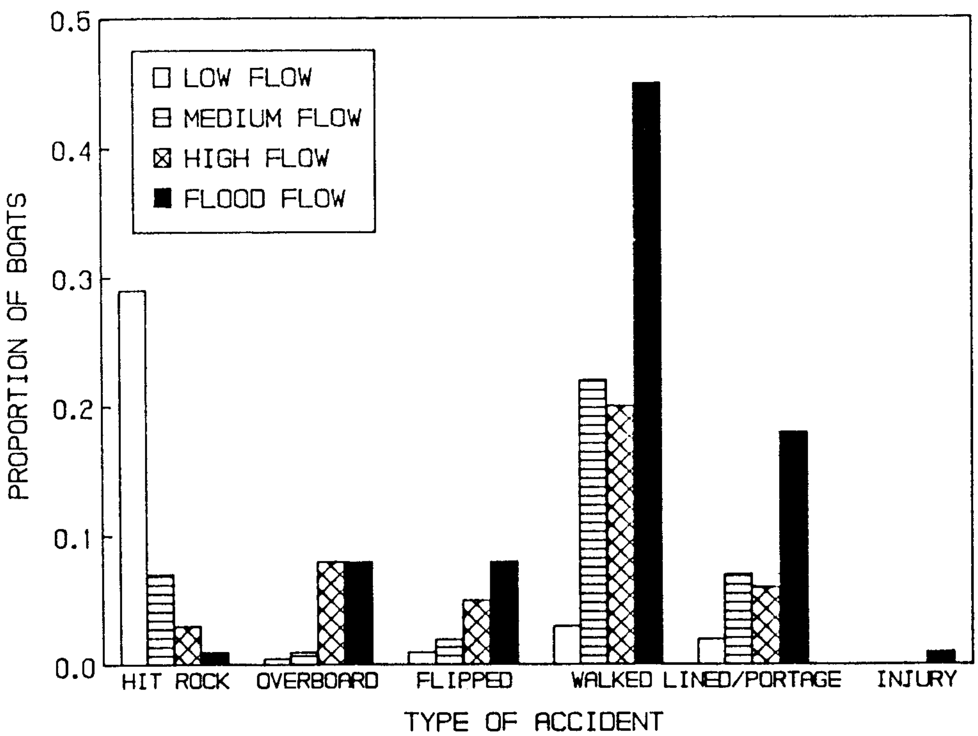

Figure 1. Accident rates at Crystal Rapid.

The chance of hitting rocks in Crystal Rapid decreases substantially and consistently as flows increase from low to flood level. The chance of going overboard and of flipping both increase from near zero at low flows to 8 percent at flood flows. A significant trend is found of more injuries at higher flows, even though the number of injuries overall is very small (zero injuries at low and medium flows, two slight and two incapacitating injuries at high flows, and three slight injuries at flood flows).

One of the most striking results is the relationship between increasing flow levels and either walking around Crystal Rapid, or portaging or lining a boat. Both of these risk management activities have frequencies near zero at low flows and increase to substantial proportions at flood flows, when nearly 45 percent of boats have passengers walk.

The results for all rapids combined are shown in Figure 2. The variables significantly related to flows are losing control of an oar, striking rocks, flipping a boat, injuries, walking around rapids, and lining or portaging boats. The combined results for the ten observed rapids are less dramatic than for Crystal

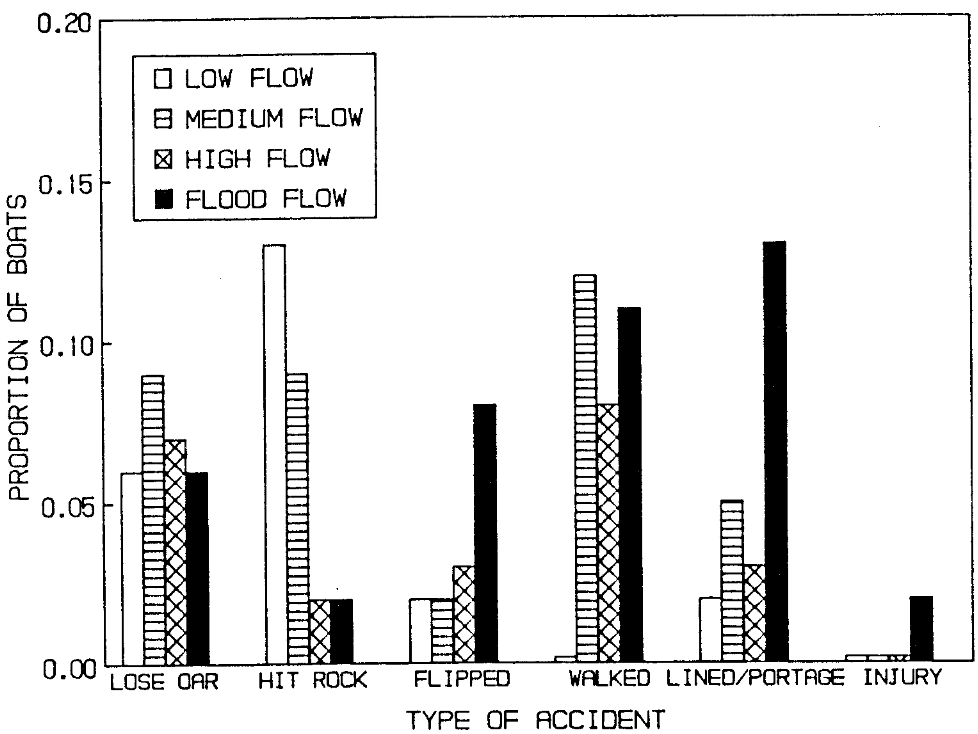

Figure 2. Accident rates overall.

Rapid alone, but follow similar patterns. For example, falling overboard follows the same pattern, but does not show a statistically significant relationship with flows.

ACCIDENTS AND LOW RIVER FLOW LEVELS. To examine the effect of low flows specifically, we assessed separately the data for Hance Rapid (River Mile [RM] 76.5) and House Rock Rapid (RM 17), two rapids that are difficult at low flows. Due to the small number of observations at low flows, the upper cutoff for the low flow category was raised to 10,999 cfs. Of the accident variables, only hitting rocks increased significantly at low flows: 26 percent of boats hit rocks at low flows, 11 percent at medium flows, and 1 percent at high flows. While the other accident variables did not show increased frequencies at low flows, it must be remembered that this analysis is based on a limited number of observations, and they were made at flows above 8,000 cfs.

ACCIDENTS AND FLUCTUATING FLOWS. Concerns have been raised that rapidly changing flows could make rapids hard to judge, particularly by less experienced boaters. To determine if river fluctuations are associated with higher accident rates, we compared accident rates during periods when flows were steady to rates during fluctuation periods (flows changing more than 10,000 cfs in 24 hours). None of the accident variables were significantly associated with fluctuations except for lining or portaging boats, which showed a slightly higher rate during fluctuations (.03 versus .02).

ACCIDENTS AND TYPE OF BOAT. The type of boat used is also related to the likelihood of accidents. In fact, in nearly all cases the relationship between boat type and accident rate is stronger than the association between flow level and accidents. For example, at Lava Falls, the range of flipping varies by .12 across flow levels, but varies by .21 across boat types. Dories and small rafts are most likely to lose control of oars. Hitting rocks is most common in large rafts, perhaps due to limited maneuverability, and in canoes. Persons are most likely to go overboard from canoes, followed distantly by kayaks and dories. Once overboard, persons from canoes have the longest time in the water, followed closely by small rafts and kayaks. Persons falling off motor rigs spend a very short time in the water, on average. Canoes are most likely of all boats to flip in rapids, with kayaks a distant second. Small rafts are observed to have the most frequent loss or damage to equipment, with dories, kayaks, and large rafts close behind. Most cases of lost equipment involved oars being lost overboard.

ACCIDENTS AND TYPE OF TRIP. The difference in accident rates between commercial and private trips is small, but consistent, averaging 2 percent higher for private trips for losing control of an oar, hitting rocks, persons falling overboard, and flipping boats. This difference may be due to the greater amount of experience commercial guides have, on average, or to a greater conservatism on the part of commercial guides, who must always consider the safety of their paying passengers first.

COMPOSITE INDEX OF RISK. To estimate the overall risk of any flow level, a composite variable was created which reflects the risk of all the types of accidents that produce personal injury or equipment damage. In creating this composite, we judged flipping a boat, losing a person overboard, a slight injury, and equipment damage as equally serious. These accidents received a score of 1. Hitting a rock was judged half as serious, with a score of 0.5 because it does not, in itself, involve personal injury or loss. Finally, an incapacitating injury was judged as twice as serious and received a score of 2. Each boat observed was scored according to this scheme and the following averages obtained for each flow category for both commercial and private trips (Table 2).

Table 2. Overall risk for commercial and private groups.

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

High flows are safest for both private and commercial trips, with medium and low flows presenting increased hazard for both. The greatest difference between the groups is found at flood flows, where the risk is much greater for private than for commercial trips. This difference in risk levels is due primarily to the more frequent use of motor rigs by commercial trips than by private groups. These boats handle very high water much more effectively than the smaller oar boats favored by private parties. The greater hazard for private trips is also reflected in the fact that a much higher proportion of private parties, compared to commercial parties, cancel their trips during high water periods.

The risk indices can be used to compare the overall risk posed by various dam operation schemes. To illustrate the comparison of yearly operating schemes, we have applied the above indices to the actual operations of Glen Canyon Dam for the years 1982, 1984, and 1986, for which the total annual dam releases were 8.2, 21, and 16.6 million acre-feet (maf), respectively. These years represent typical operations under a wide range of seasonal runoff conditions. The overall risk indices for the actual river flows in 1982, 1984, and 1986 are shown in Table 3. To provide context for interpreting these yearly indices, Table 3 also shows the indices produced by hypothetical years comprising flows exclusively in one flow range.

Table 3. White-water risk indices for 1982, 1984, and 1986 for actual Glen Canyon Dam operations.

Year	Risk Index
1982	1,304
1984	1,079
1986	1,001
All Low Flow	1,688
All Medium Flow	1,232
All High Flow	797
All Flood Flow	1,409

The most hazardous year was 1982 followed by 1984 and 1986. Somewhat surprisingly, the risk index is not linearly associated with the total acre-feet passed through the dam. Due to the preponderance of commercial trips each year, the overall index is dominated by the risk indices for that group. Therefore, the overall risk index is most influenced by the amount of low flows in a year, since these are most hazardous for commercial parties. The year 1982 had the most hours of low flows during the rafting season and therefore has the highest risk index.

The comparison of 1984 and 1986 illustrates the importance of time of year in determining the hazard associated with a given flow level. The year 1986 has a somewhat lower hazardous rating of the two, even though it contained some low flows while 1984 had none. Because most of those low flow hours fell outside the main rafting season (May to September), they do not impact the overall index significantly. This, and the fact that 1984 had more flood flows in the main rafting season, caused it to receive a more hazardous overall rating than 1986.

DISCUSSION

The relationships between accidents and flows reported here, in addition to being statistically reliable, are supported by multiple types of data (expert judgement, historic records, direct observations) and show a consistent pattern. Thus, we are confident that the relationships are real. Further, while a correlation between flows and accidents cannot prove a causal relationship, we can find no plausible explanation for the observed association other than that differences in flow level cause differences in accident rates.

Interpreting the practical significance of the results is less straightforward. Do changes in flows increase boating hazard enough to warrant control of flows in the interest of safety? If so, how much should flows be controlled? How much risk is acceptable, even desirable to boaters?

These are questions that must be answered jointly by managers and white-water boaters. While boaters have indicated that they find some flow levels "too risky," they also believe that challenge and danger are an integral part of the white-water experience. The review of this data by white-water boaters must be a central part of the evaluation of its significance.

Similarly, managers must consider their policies and responsibilities for risk management. Currently, white-water boaters in Grand Canyon are required to meet Coast Guard safety standards for equipment. In June 1983, high flows caused several accidents at Crystal Rapid, with three motor rigs flipping, two other boats destroyed, and over 100 persons evacuated. In response to these accidents, the Park Service instructed boaters to walk around rather than run Crystal Rapid. During the highest flows (over 92,000 cfs) the river was closed to boaters. These management actions suggest a recognition by managers of a federal responsibility for risk management, but do not define the limits or the basis for such responsibility. Consideration of these issues, jointly with the affected recreation groups, could create a more comprehensive policy framework within which to select and apply risk management options.

CONCLUSIONS

River flows were studied within the range of 3,000 to 50,000 cfs. Within these ranges, we conclude that: (1) river flow level affects accident rates; (2) flows in the range 10,000-17,000 cfs are the safest of the flows evaluated when considering together type of boats, boats hitting rocks, and equipment damage; (3) falling overboard, flipping boats, and injuries increase with increasing flows; (4) generally, hitting rocks declines as flows increase; (5) actions taken to avoid rapids (walking passengers around rapids, portaging and lining boats) increase as flows increase; and (6) river fluctuations by themselves do not appear to increase the rate of accidents.

BOATING ACCIDENTS AT LEES FERRY: A BOATER SURVEY AND ANALYSIS OF ACCIDENT REPORTS

This is a summary of studies conducted on the accident rates of Glen Canyon anglers and day-use rafters above Lees Ferry, Arizona, within the Glen Canyon National Recreation Area.

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INTRODUCTION

The study area consists of approximately 15 miles of the Colorado River from Lees Ferry to Glen Canyon Dam. It is located within Glen Canyon National Recreation Area, which is administered by the U.S. National Park Service (NPS). Recreational opportunities include boating, fishing, camping, hunting, and commercial float trips. Trout fishing is the most popular recreational activity. Boat types used on the river range from small, open, aluminum fishing boats with outboard engines to fiberglass runabouts with inboard engines. Hull sizes range between 9 and 24 ft with the 12- to 16-foot aluminum car top fishing boat predominating. Most boating occurs in the form of day trips between sunrise and sunset.

In April 1986, a study by Underhill, Hoffman, and Borkan (1986) of the Cooperative Park Studies Unit at the University of Arizona was initiated to determine if there is a significant correlation between reported boating accident occurrence and the river flows at the time and place of the accident. The study looked at eight accident variables: dates, time, location, commercial or private operator, accident type, flow at time of accident, boat type, and boat size. Flows were categorized into four flow ranges:

Low = less than 9,000 cubic feet per second (cfs)
Medium = 9,000-15,000 cfs
High = 16,000-31,500 cfs
Flood = greater than 31,500 cfs

A total of 29 usable accident reports from the study period formed the basis for the analysis. A mix of 14 NPS case incident and 15 NPS boating accident forms were used. Information on the forms varied greatly. They all, however, supplied date, time, and location of the boating accident.

Underhill et al. concluded that although flow-related trends were found for boating accidents in Glen Canyon, the small number of reported accidents and the lack of sufficient information on other accident-related variables made reaching any flow-related conclusions questionable. However, they did note that although they thought the flow ranges used were reasonable, the use of different flow ranges might result in a different and non-random distribution of accidents. The fact that 69 percent of all Glen Canyon boating accidents occurred in the high flow range, which accounted for only 40 percent of the total boating hours, suggested some undetermined connection between flows and accident occurrence in that flow range. They postulated one possible interpretation of the descriptive analysis of non-flow-related factors and overall non-random distribution: boaters were more likely to have problems which resulted in accidents during high flows and much less likely to have such problems during medium and low flows.

The Underhill study raised several questions which needed to be answered. The findings seem to indicate that more variables were involved than just a static flow level and the occurrence of an accident at a specific location. What are those variables and how do they interact with flows, if at all? Are accident reports representative of the accidents that occur in the study area? How does the accident rate, which as computed appeared to be so small as to be insignificant, compare to the national average and other locales with similar situations? The study looked at three representative years of data. The small sample size appeared to hamper the analysis. Would a larger sample size provide a better database? This study attempted to address these questions.

METHODS

The study was divided into two major components. The first was a survey of boaters at Lees Ferry to determine an accident rate and to compare actual accidents to reported accidents. This survey consisted of a short questionnaire administered by HBRS, the U.S. Bureau of Reclamation contractor conducting recreation research for the Glen Canyon Environmental Studies. They administered this questionnaire along with the Lees Ferry Fishermen Survey they were conducting, on the same days and to the same parties, although not to the same people. None of the accidents reported by survey respondents were reported to the NPS.

The second component was an extension of the Underhill study by doing the following:

1. Extending the study period to cover eight years (1977-1984) of data by gathering and analyzing all accident reports during that period. This would cover all usable accident reports on file at Glen Canyon National Recreation Area and provide a larger database from which to work.

2. Examining additional accident factors recorded on accident reports, including all the data on the National Park Service boating accident report form.

3. Using a factor analysis to examine accident occurrence in relation to flows in order to determine if any "problem" flow ranges could be determined by the data.

4. Examining river flow fluctuation prior to the accident in an effort to determine what flow-related factors, other than flows at the time of the accident, may have contributed to accident occurrence.

All boating accident reports in the files at Glen Canyon National Recreation Area were reviewed, and those dating from 1977 to the present were found to be the most useful. Data gathered from the reports include date, time and location of the accident; type of accident; reported cause; wind; operator age and experience; size and type of boat; engine size in horsepower; boat operation at the time of the accident; water and weather conditions; and whether the accident occurred during the day or night. Bureau of Reclamation records on Glen Canyon Dam releases were used to determine the flow both at the time and location of the accident and hourly for the previous four-hour period. All accident data were codified numerically and entered into the computer spreadsheet for later statistical analysis. There were several reports for which some accident variables were unknown.

Originally the Resources Management Branch at Glen Canyon National Recreation Area, which was responsible for data collections, was to be assisted by representatives of the Bureau of Reclamation in doing the computer analysis, especially the statistical portion of the project. Unfortunately, due to the time limitations and scheduling conflicts, the statistical analysis was not accomplished before the report deadline. This report will therefore be restricted to a descriptive analysis of the data.

RESULTS

ACCIDENT SURVEY. During the 64 days of data collection between April 29, 1984, and December 19, 1985, a total of 355 parties were surveyed of which 342 filled out questionnaires for a response rate of 96 percent.

There were 21 reported accidents during the survey, indicating that 6 percent of the respondents experienced a problem of some type during their boating trip at Lees Ferry. Of those reporting accidents, 86 percent (n=18) reported damage to propellers only, 10 percent (n=2) reported running out of gas, and 5 percent (n=1) reported being swamped. One party reported damage to two different propellers on the same boat on one day. One propeller was reported destroyed and the other damaged. This was treated as one accident since only one location and the total value loss was reported. Another party reported damage to both the boat and the propeller. This also occurred at the same location and time and was treated as one accident. It was recorded as propeller damage only because the available information indicated that all damage resulted from one incident and the type of boat damage could not be determined.

Accidents were reported on 11 of the 64 days of the survey. All but three of the days with accidents were in October, November, and December of 1985. That period coincided with the fluctuating flow regime being released at the dam for the Glen Canyon Environmental Studies. During that period, river flows were fluctuating in the low range (0-9,000 cfs) for about 30 percent of the time. Flows were in the medium range (9,000-16,000 cfs) 47 percent of the time and in the high range (16,000-31,500 cfs) 23 percent of the time. Prior to that, flows were high (+20,000 cfs) and constant with relatively little fluctuation. During the high, constant flow period, there were two cases of people running out of gas and one incident of propeller damage. During the low, fluctuating flow period, 86 percent of the accidents occurred, including 15 incidents of damage to propeller, one damage to propeller and boat, and one swamping. The accident rate for the fluctuating flow period was 2.5 times the overall rate, with 15 percent of the 122 respondents surveyed reporting incidents.

Eight respondents (38 percent) of those reporting accidents gave times for their accidents, and only four of those indicated a specific time. All the others said that their accidents occurred in the morning. Of those that indicated times, two reported accidents in the morning, one at noon, and the other at 2:00 PM.

Ten respondents indicated a location of their accident, with 70 percent (n=7) reporting Three-Mile Bar and one each reporting Four-Mile, Six-Mile, and Ten-Mile, respectively. Four-Mile could be a misidentification of Three-Mile Bar since River Mile 0 at Lees Ferry is shown to be about one mile downstream from the original ferry site on some maps. Both Six-Mile and Ten-Mile have wide, shallow portions of the channel due to bends in the river. Though direction of travel was not indicated in the questionnaire, the preponderance of morning incidents suggests that the direction of travel at the time of accidents may be mostly upstream.

Estimates of damage cost were reported by 16 respondents. These ranged from $25 to $200 with an average loss of $86. The loss estimates appear to be evenly spread throughout the range, with 31 percent (n=5) reporting losses of $100-200, 31 percent (n=5) reporting losses of $25-50, and 38 percent (n=6) reporting losses of $60-70. The value of loss by accident type is $50 for boat damage (n=1), $200 for lost equipment from the swamped boat (n=1), and a range of $25-200 (average loss of $75) for propeller damage (n=15).

A check of NPS records indicates that during the survey period, two boating accidents were reported at Lees Ferry. On May 18, a boat flooded and capsized due to the operator dragging anchor while fishing in the fast river current. The other accident occurred on May 20 when a motor lost power and the boat drifted past Lees Ferry and into the riffles below. The boat and operator were rescued by NPS Rangers with no injury or damage. Those involved in both incidents were not surveyed, since data were not collected all day every day. Data from those accidents are not being used in this portion of the report.

BOAT ACCIDENT REPORT DATA. The following analyses are from data compiled from National Park Service Lees Ferry boating accident reports. Several of the reports lacked data for all the accident factors and some accidents were reported with multiple response factors. A total of 56 accidents were evaluated. However, because of the multiple responses and the lack of available information in some reports, the number of accidents used in each portion of the analysis may total more or less than 56.

The most recent statistics available from the Coast Guard (1985) indicate that the boat types most often used at Lees Ferry, when combined, have produced an accident rate of 1.27 accidents per million passenger hours. When this rate is compared to the Lees Ferry boating accident data, it appears that Lees Ferry has an accident rate almost 17 times the national average. However, Coast Guard figures represent reported accidents only. The Coast Guard (Traub, pers. comm.) estimates the reporting rate of non-fatality accidents to be only 5 to 10 percent. Assuming this to be the case, the adjusted national rate would be from 12.7 to 25.4 per million passenger hours. The National Park Service estimates a reporting rate of 90 percent for accidents under the U.S. Coast Guard criteria and 5 to 10 percent for minor incidents. Consequently, the Lees Ferry accident rate of 17.7 is more in line with the adjusted national average.

In 70 percent of all the accidents (n=39), a change in flows occurred one to three hours before the incident (Table 1). The percentage increases to 80 percent (n=45) if the period is extended to four hours before the accident. In that four-hour period, a mean of 73 percent of the cases experienced a change in flows (56 percent experienced an increase in flows, and 17 percent experienced a decrease in flows). A mean of 27 percent of the cases experienced no change in flows. The percentages stay relatively constant for each hour of the four hours prior to the accidents.

The change in flows for each hour ranges from a maximum decrease of 3,255 cfs to a maximum increase of 8,446 cfs over the four-hour period. One hour before the accidents, 25 percent experienced a 1,000 cfs increase in flows, 20 percent experienced a 2,000 cfs increase in flows, 7 percent experienced a 3-4,000 cfs increase in flows, and 2 percent experienced a 7,000 cfs increase in flows. Conversely, for the hour before the accident, 11 percent had a 1,000 cfs decrease in flows, and 4 percent had a 2-3,000 cfs decrease in flows. These percentages stayed approximately the same for each of the four hours before the accidents.

Table 1. The cfs change in flow by hour before reported accidents by number of accidents.

CFS Change in Flows	Hours Before an Accident -1 Hr	-2 Hr	-3 Hr	-4 Hr
-3000	1	0	0	1
-2000	1	2	4	2
-1000	6	12	4	5
0	17	16	17	11
+1000	14	16	10	14
+2000	11	3	7	10
+3000	3	1	6	5
+4000	1	1	3	1
+5000	0	3	2	3
+6000	0	1	1	1
+7000	2	1	1	1
+8000	0	0	0	1
+9000	0	0	1	1

Two hours before the accidents, 29 percent experienced a 1,000 cfs increase in flows, 5 percent had a 2,000 cfs increase, 4 percent had a 3-4,000 cfs increase, and 9 percent had a 5-7,000 cfs increase. Moving out to three and four hours before the accidents, the increase in flows moves toward the greater ranges. At three and four hours before the accident, 14 percent of the cases experienced a 4-9,000 cfs increase each hour.

DISCUSSION

The accident rate for Lees Ferry appears to be comparable to the national average and does not appear to be skewed by the river flows. The most frequent type of accident appears to involve minor propeller damage as a result of hitting a gravel bar in the morning during a period of fluctuating flows. It has an average damage loss of $86 and is not reported. Approximately 5 percent of all accidents are reported to the National Park Service. Of those, the most common accident appears to be the capsizing of a 12- to 14-foot fishing boat which is cruising in strong current on a clear day with little to no wind and is being operated by a person with 21-500 hours of boating experience.

The accident survey covered periods of both high, steady flows and low, fluctuating flows. Accidents reported during the survey were more frequent during the low, fluctuating flow period. The data were not available to determine if these incidents were the result of fluctuating flows, low flows, or a combination of both. It is also not possible with the existing database to determine if boaters experiencing a period of low, fluctuating flows after a long period of high, steady flows had an effect on the data, or, if so, the magnitude of that effect.

Accidents reported during the survey were primarily low cost and involved property damage with an average loss of $86. None of these accidents were reported to the National Park Service for inclusion in the accident reporting system. Only two accidents were reported to the National Park Service on the data collection days. Only one of these was flow-related and occurred during the high flow period. This appears to confirm the belief of National Park Service Rangers that they primarily hear about or become involved in only the most serious or life threatening accidents.

CONCLUSIONS AND RECOMMENDATIONS

It is unfortunate that a more thorough analysis could not be completed. As a result, no statistical significance could be used to determine a cause and effect relationship, if any, between flows or change in flows and boating accidents. The low number of accidents identified in both the survey and the accident report analysis also makes drawing conclusions difficult.

The survey identified a high number of minor property damage accidents which occurred during predominantly low, fluctuating flows and at known gravel bars in the river. Operator experience with and forewarning of these conditions is unknown. The accident reports covered the more serious property damage and injury-involved incidents. Underhill found a significant number of accidents occurring at high flows. The longer-term data of this study seemed to support that finding. In addition, changes in flow and/or boat operation at the time of the accident appeared in a large number of cases. Large fluctuations in flows appeared to be more important than previously thought. However, the total flow regime and the number of boaters exposed to that regime need to be determined. What sort of boater education might be needed? Are boaters being provided with adequate information about expected flows?

SIMULATING THE EFFECTS OF DAM RELEASES ON GRAND CANYON RIVER TRIPS

The Lucas-Shechter Wilderness Use Simulation Model (WUSM) was modified to simulate the effects of Glen Canyon dam releases on river trips through Grand Canyon National Park.

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INTRODUCTION

The Lucas-Shechter Wilderness Use Simulation Model (WUSM) (Shechter 1975; Shechter and Lucas 1978) was modified in order to determine the effects of Glen Canyon Dam releases on Colorado River boat trips through Grand Canyon National Park. Five alternative flow regimes proposed by the U.S. Bureau of Reclamation were tested. The output of the Streamflow Synthesis and Reservoir Regulation (SSARR) model for the Colorado River was used as input into the WUSM.

Releases from Glen Canyon Dam control the flow of the Colorado River through Grand Canyon National Park. The effects are most pronounced nearest the dam and diminish downstream with increasing distance. Grand Canyon river trips start at Lees Ferry (River Mile [RM] 0), approximately 15 miles below the dam. Even at Lees Ferry there is some attenuation of river flow. A peak dam release may take up to 24 hours to reach Phantom Ranch (RM 88), and over two days to reach Diamond Creek (RM 225). Dam releases produce different flow levels at different locations. During the same day, the flow at Lees Ferry may vary between 3,000 cubic feet per second (cfs) and 30,000 cfs, and the flow at Crystal Rapid (RM 98) between 5,000 cfs and 20,000 cfs.

The most obvious effect of dam releases on river trips is the fluctuation of the river level. Velocity of the river flow, which increases in proportion to the volume of water released, is also important because velocities influence the rates boats travel. We studied the effects of dam releases ranging from 1,000 to 35,000 cfs. The model simulated flows at specific locations at specific times, independent of the flow of the previous hour. In other words, the model does not consider whether the river is rising or falling. It is the flow at a particular location at a specific time which is of primary interest. The effects of very rapid changes in water releases on river velocity and turbulence were not quantified, and therefore not simulated. Nor was the beaching of boats which may occur due to reduced river level.

The WUSM incorporates as many of the salient features of Grand Canyon river trips as possible. This model has approximately 3,000 lines of General Purpose Simulation System (GPSS) computer code. As in most computer models, simplifying assumptions had to be made to transform reality into computer code. Important assumptions are noted and discussed.

METHODS

The WUSM was originally designed under the premise that user satisfaction in wilderness areas was inversely proportional to the number of encounters with other parties. It was designed to simulate travel through a wilderness trail system, with outputs of: (1) the number of encounters with other parties; (2) the locations where they occur; and (3) the use of campsites, attraction sites, and trail segments.

The original WUSM had two types of users: hikers and riders. Underhill and Xaba (1983) changed these users to oar-powered and motor-powered river parties. The trail system of the original model became the Colorado River through Grand Canyon National Park, including the river from Lees Ferry to Diamond Creek (approximately 225 river miles) and all possible stops. These 225 miles were divided into 199 river segments by campsites, attraction sites, and other possible stops. In all, there were 110 attraction sites and 140 campsites in the model. All river segments and attraction sites had an associated travel or visit time (Shelby and Nielsen 1976a-d). The single trailhead was Lees Ferry, and the two exit points were Whitmore Wash and Diamond Creek.

River trip lengths were from 5-18 days: 5-11 days for motor trips, and 12-18 days for oar trips. Simulated trips had preplanned itineraries, unlike actual trips. All Grand Canyon river trips are permitted by the National Park Service (NPS) for a specified length of time. However, within that trip's duration, the party is free to choose where it camps and what attraction sites it visits. The WUSM was unable to do this, so preplanned itineraries were its first assumption.

River trip itineraries were developed by a computer program which utilized actual frequency of use data of attraction sites and campsites from 1980-1983 (Underhill and Xaba 1983). The itineraries used in the model were representative of typical trips taken in Grand Canyon, and the launch schedule was the actual one administered by the NPS in 1984. For this study, lines of code were added which made it possible to include the effects of river flow on simulated raft trips.

The WUSM simulated party departures from Lees Ferry according to a launch schedule (the number of trips, their trip duration, and the type: oar or motor). Parties proceeded downstream according to their itineraries (which were chosen at random based on trip duration and mode of travel). The program simulated five weeks. During the first two, parties proceeded downstream to initialize the run; for the remaining three, all encounters, use of all river segments, campsite arrival times, and delays at rapids were recorded for each simulated week.

The following five flow alternatives were developed and tested on the model:

Alternative 1. Releases would be baseloaded with no daily fluctuations in any given month. Monthly flows would vary, ranging from 8,300 cfs in March to 14,600 cfs in January.

Alternative 2. Flows would fluctuate daily, monthly, and seasonally, ranging from 1,000-31,500 cfs. Average monthly releases would range from 8,300 cfs in March to 17,000 cfs in July.

Alternative 3. Average amount released each month would be similar to that in Alternate 2, but with higher minimum and lower maximum releases. Flows would range from 8,000-25,000 cfs.

Alternative 4. Releases would be a steady 25,000 cfs during the recreation season (June-August), but would fluctuate from 1,000-31,500 cfs the remainder of the year. Average monthly flows would range from 4,900 cfs in March, May, and October, to 25,000 cfs in summer.

Alternative 5. Designed to benefit the fishery, this release pattern features low, relatively steady winter flows, averaging 8,000-8,900 cfs per month, fluctuating only 6,000-10,000 cfs. Most of the rest of the year, flows and fluctuations would be greater, with average monthly releases ranging from 12,200 cfs in May to

17,000 cfs in July. Fluctuations would also be greater, ranging from 1,000 to 31,500 cfs.

The five alternatives included hourly dam releases for both weekdays and weekends (traditionally, weekend releases are lower). Each of the five scenarios had a dam release prescription for each of the 12 months of the year. Within each month, every week was identical. For each flow scenario, the SSARR model computed hourly river flow at 11 downstream locations, consisting of five days of weekday flows, then two days of weekend flows. The flows selected for the model were from the middle of the month, starting on a Sunday and ending on a Saturday, insuring that the full effect of the scenario was felt along the entire length of the river.

River flows affect the navigability of rapids and the speed of river travel. In the WUSM, river segments were assigned to the closest of the 11 flow stations, then the flow at each segment was determined by date, time and location. The WUSM followed each party and as it reached a segment, checked the date and time, recorded the flow, and computed a speed factor. For example, if a river party arrived at Segment 65 at 1000 hours on Monday, July 2, the model checked the Little Colorado flow station to determine the flow at that time. Speed factors were different for oar and motor parties, as shown below. Straight-line interpolation was done by the model among these four flow values:

	Oar Speed Factors	Motor Speed Factors
1,000 cfs	3.0	2.0
5,000 cfs	2.0	1.7
16,500 cfs	1.0	1.0
35,000 cfs	0.8	0.8

The travel times in the model were based on a steady flow of 16,500 cfs, with a factor of 1.0. Motor and oar trips increased their speed proportionally at higher flows. Lower flows slowed oar trips more than motor trips.

For simulated motor trips, speed of travel was the product of travel time and the speed factor. For simulated oar trips, travel time on the river and at attraction sites was 1.75 times longer than for motor trips (Underhill and Xaba 1983). Therefore, speed of travel for oar trips was computed by multiplying the speed factor by the travel time and 1.75.

River flow also determines whether a particular river segment is traversable. Of the 199 river segments, 24 are rapids where delays can occur. In actuality, when faced with low flow at a rapid, the boatman determines whether: (a) the party walks around the rapid while he navigates the boats through, (b) they wait for higher water, or (c) they float the river segment without hesitation. This decision process includes consideration of the expected rise or fall of the river over the next few hours, trip length, time of day, and location. Data were not collected on these variables, so the model was not programmed to make this decision. For this study, it was decided that all parties in the model would handle a delay at a rapid exactly the same way in each simulation.

Two methods were used. In the first method, called the WALK routine, if a party was scheduled to travel a rapid at a water level below the benchmark flow for their boat type, the party waited for one hour, during which time the passengers either walked around the rapid or decided to run the rapid at the present level. After one hour, the boats proceeded through according to the time allotted for that river segment. In the second method, called the WAIT routine, the party waited for the water to rise above the benchmark flows regardless of how long the wait. The exception to the WALK and WAIT routines was Horn Creek Rapid. Some of the alternatives would have delayed parties there for days since the flow would never have allowed parties to proceed. For the purposes of comparison, when a party was delayed at Horn Creek, the WALK routine was always used. It is not important that in reality one cannot walk around Horn Creek Rapid. The idea was that the party was delayed by low water. Because boatmen knew higher flows were not forthcoming, the trip proceeded.

The data from the WALK and WAIT simulations were combined to present results during which half of the time the party walked around the rapid, and half of the time the party waited for higher water. In some cases, this meant waiting for hours. Averaging these provided a useful comparison of alternative flow scenarios.

Navigation information was gathered by the "expert witness" method of data collection. Information was obtained from boatmen who had a minimum of five years experience on the river, and thus knew river conditions at low water.

Rapids were assigned to seven classes based on their characteristics at particular flows. Class 1, to which most rapids were assigned, were those through which motors, oars, and dories could be successfully navigated at flows over 1,000 cfs. Classes 2-7 were assigned to rapids where delays would occur if the flow were below that listed for a particular boat type. There are 24 rapids in Classes 2-7.

Two simulations, one using the launch schedule from May 1984, and the other using the schedule from July 1984, were run for the five flow regime alternatives. The July schedule represented the peak river running months of June through August, while the May schedule represented the shoulder seasons of May and September. Data were produced for six weeks in each simulation: three using the WALK routine, and three having the parties wait for higher, safer water.

RESULTS

THE JULY SIMULATION. The peak rafting season in Grand Canyon encompasses the summer months of June, July, and August. Between July 1 and August 4, 1984, 186 trips were launched from Lees Ferry. An average of 3.5 trips departed on Thursdays and Fridays, with higher launch rates the rest of the week.

The July scenarios for Alternatives 2 and 5 were identical, so for the remainder of this report, the July results for Alternative 2 represent both Alternatives 2 and 5. The range of releases for the July alternatives are listed below in cfs.

	Weekdays	Weekends
Alternative 1:	12,750 constant	12,750 constant
Alternatives 2 & 5:	6,600 - 31,500	3,600 - 23,400
Alternative 3:	8,500 - 25,000	8,500 - 26,700
Alternative 4:	25,000 constant	25,000 constant

Simulation of each of these four alternative flow scenarios provided data on the time available for attraction site visits, delays at rapids, and encounters with other parties on the river, at attraction sites, and in camp.

The effects of the four alternative July scenarios did not vary greatly (Table 1). Alternative 4, with constant releases of 25,000 cfs, allowed the most time for attraction site visits; an additional 15 minutes could be added to attraction site visits/party/day under this alternative. Under the other alternatives, parties would have to reduce their visit time by from 56 to 92 min/party/day in order to achieve the mean campsite arrival time of 1630 hours. Alternative 4 also had the highest percentage of parties in camp between 1500 and 1800 hours (62.3 percent).

None of the four July scenarios resulted in a party being delayed at a rapid. Encounter rates among the four alternatives were very similar, although Alternative 4 consistently had a slightly higher level

Table 1. Summary of the effects of the July alternatives on simulated river trips.

		July Flow Alternative		
	#1	#2,#5	#3	#4
Times and Rapids				
Average reduction (increase) in attraction site visit time (in min)	92	63	56	(15)
Mean campsite arrival time (in hours)	1802	1733	1726	1615
Percent of arrivals between 1500 and 1800 hours	45.8%	49.4%	52.7%	62.3%
Number of delays at rapids	0	0	0	0
Encounters				
Eight attraction sites				
- on-site	9.74	10.67	10.46	12.21
- off-site	12.85	12.88	13.82	13.85
Average number of river and attraction site encounters per party per day (PPPD)				
- on-site	4.55	4.35	4.43	4.69
- off-site	4.33	4.64	4.69	4.67
Average number of camp encounters PPPD - on-site	0.74	0.70	0.79	0.79
- off-site	0.85	0.91	0.85	0.87
Total average number of encounters experienced PPPD	10.5	10.6	10.6	10.8

of encounters on the river and at attraction sites. The fluctuating scenarios (2 and 3) had fewer encounters, and Alternative 1, with a constant flow of 12,750 cfs, had the fewest.

THE MAY SIMULATION. A significant number of both commercial and private trips raft the Colorado River through Grand Canyon National Park during the spring and fall. In May 1984, 127 trips launched from Lees Ferry. A similar number launched in September. The month of May was simulated in order to determine the effects of different releases on significant numbers of parties.

Three of the five May scenarios had releases at or below 3,000 cfs. As expected, there were more delays at rapids and significantly slower travel through the canyon.

For the May launch schedule (May 1-June 4, 1984), an average of 18.5 trips departed each week during the first two weeks. An average of 29.67 trips were launched each week during the final three weeks. Again the number launching Thursday and Friday was lower than during other days. The May releases for each of the five alternatives are summarized below, with flows stated in cfs.

	Weekdays	Weekends
Alternative 1:	10,000 constant	10,000 constant
Alternative 2:	2,200 - 13,500	3,000 - 10,700
Alternative 3:	8,000 - 11,300	8,000 - 11,500
Alternative 4:	1,000 - 31,000	1,000 - 30,000
Alternative 5:	3,000 - 20,900	3,000 - 10,800

Table 2 summarizes data for parties operating under the five May flow alternatives. Four had mean campsite arrival times between 1805 and 1846 hours. As the mean campsite arrival time got later in the day, the percent of arrivals between 1500 and 1800 hours became smaller. To achieve a mean campsite arrival time of 1630 hours, at least 90 min would have to be taken from attraction site visit times for each day. Alternative 4 had a mean arrival time of 1509 hours, but only 10 percent of all parties arrived in camp between 1500 and 1800 hours. Parties arrived in camp at all hours of the day and night under this alternative due to substantial delays at rapids and slow river travel. Obviously actual trips would have compensated for this, but the model can only illustrate the effects without compensation.

Table 2. Summary of the effects of the May alternatives on simulated river trips.

	May Flow Alternative				
	#1	#2	#3	#4	#5
Times and Delays					
Average reduction in attraction site visits (in min)	129	122	136	*	95
Mean campsite arrival times (in hours)	1839	1832	1846	1509	1805
Percent of arrivals between 1500 and 1800 hours	32.4%	24.4%	25.7%	10.2%	37.1%
Number of delays at rapids	0	229	90	1076	124
Average time spent delayed per occurrence (hours)	0	1.46	1.00	2.96	1.60
Average number of delays per party	0	2.50	1.00	11.96	1.38
Average time spent delayed per party (hours)	0	3.65	1.00	35.40	2.21
Encounters					
Eight attraction sites: on-site	7.36	6.96	7.90	6.05	8.26
off-site	10.36	9.60	10.01	10.67	10.56
Average number of river and attraction site encounters PPPD on-site	3.60	3.63	3.62	3.48	3.67
off-site	3.78	3.87	3.78	3.91	4.01
Average camp encounters PPPD on-site	0.53	0.61	0.54	0.66	0.56
off-site	0.78	0.95	0.78	1.64	0.87
Total average number of encounters experienced PPPD	8.69	9.06	8.72	9.69	9.11

* = exact amount not determined, highest of all alternatives tested.

Alternative 1, with a constant release of 10,000 cfs, delayed no parties at rapids. Alternatives 2, 3, and 5 delayed parties from one to four hours during their entire trip. Alternative 4 produced 1,076 delays, averaging three hours each, for a total of 35 hours/trip.

Alternative 1 had the least number of encounters experienced/party/day (8.69); Alternative 3 was next at 8.72; 2 at 9.06; 5 at 9.11; and Alternative 4 had the most at 9.69. Alternative 4 had one more off-site (visual) camp encounter than the other alternatives, probably due to the odd hours of camp arrivals.

DISCUSSION

Simulation of the dam release alternatives revealed a number of trends. First, the lower the release, the slower a party traveled, and consequently the less time available for attraction site visits. A component of slow travel time not incorporated in the WUSM was the human dimension. Oar parties row more at low flow, and when combined with upriver winds, low flow oar travel can come to a standstill. For motor parties, low river flow requires longer motor use and more fuel, subjecting passengers to more motor noise and odor.

Second, as flows got lower, more delays occurred at rapids. How a boatman on the river responds to these delays is an individual decision. Most trips, particularly commercial trips, must stay on a schedule. Schedule concerns are generally greater for shorter trips than longer trips.

A third trend concerned encounters. The number of encounters that a party experienced was more dependent upon the launch schedule than upon the river flow. Tests done previously with this simulation model have shown that encounter levels could be reduced 25 percent and more by spreading the number of launches evenly throughout the week, and by not launching trips of the same length on the same day (Underhill et al. 1986). Except for low flows which delayed parties at rapids, fluctuating flows produced slightly lower encounter rates on the average than did steady, high flows. This may be due to the fact that fluctuating flows tend to space parties out, whereas steady flows keep everyone going along at approximately the same rate.

THE JULY SIMULATION. The steady release of 25,000 cfs in Alternative 4 would increase the amount of time available for attraction site visits. This alternative provided one hour or more additional attraction site visit time per day over the other July scenarios. Alternatives 2, 3, and 5 produced more attraction site visit time than Alternative 1, which produced the least.

Encounter rates/party/day for the four July scenarios were similar, all producing approximately 10.5 encounters/day (1.5 in camp). Encounters were divided equally between on-site and off-site encounters. There were no delays at rapids in any of the scenarios. Subjecting the July 1984 launch schedule to these four alternative flow regimes indicated that all were satisfactory, although there were differences in the amount of time available for attraction site visits, as well as very slight differences in encounter rates.

THE MAY SIMULATION. Attraction site encounter rates in the five May alternatives were similar, with Alternative 4 having the least on-site and the most off-site encounters. However, since Alternative 4 had parties arriving in camp at all hours of the day and night, parties were also visiting attraction sites at odd hours, thereby not encountering other people.

The average number of encounters/party/day was also similar, averaging 8.9 on the river and at attraction sites (1.4 were in camp). The May alternatives had approximately 20 percent fewer encounters/party/day than did the July scenarios, supporting the argument that encounter levels are more dependent upon the number of parties launched than upon river flow.

The major issue with the May scenarios was the delays at rapids. Alternative 1, with a constant release of 10,000 cfs, did not delay parties at rapids. Alternative 3 only delayed parties at Horn Creek. Alternative 5 delayed parties at Soap Creek, House Rock, Horn Creek, Bedrock, Deubendorff, and Tapeats. Alternative 2 delayed parties at Soap Creek, House Rock, 24.5/25 Mile, Horn Creek, Waltenberg, Forster, Bedrock, Deubendorff, and Tapeats. Alternative 4 delayed parties at all 24 rapids, producing more delays at rapids than any other alternative studied. It also reduced the available attraction site visit time the most.

In order to achieve a mean campsite arrival time of 1630 hours, all trips operating under these May alternatives would need to reduce their attraction site visit time by a minimum of 90 min/day. For Alternative 4, large itinerary changes would have to be made in order to keep a party on a diurnal schedule. Trip itineraries in the model provide sufficient time for each attraction site visit, and a number of visits each day. Even when attraction site visit times are shortened by as much as two hours per day, there is still time for visits.

Alternative 4 had greater impacts upon river trips than any other scenario tested. The other four May alternatives did affect river trips in terms of time at attraction sites, encounters with other parties, and delays at rapids; however, their effects were marginal compared with those of Alternative 4.

CONCLUSIONS AND RECOMMENDATIONS

In evaluating flow scenarios, the simple rules are: (1) the higher the flow, the more time that is available for attraction site visits, (2) the lower the flow, the greater number of parties delayed at rapids, and (3) the greater the number of parties launched, the greater the encounter rates.

ALTERNATIVE 1. With constant releases as low as 8,300 cfs in March to a high of 14,600 cfs in January, this alternative would produce the following effects on river trips: (1) slow river travel; (2) reduced attraction site visit times; and (3) no delays at rapids, with the exception of Horn Creek.

ALTERNATIVE 2. With daily releases fluctuating between 1,000 and 31,500 cfs during September and May, and between 3,000 and 31,500 cfs June through August, this alternative would provide: (1) fewer encounters than a high, steady flow alternative; (2) less attraction site visit time; and (3) parties delayed at rapids during non-summer months.

ALTERNATIVE 3. With daily fluctuations between 8,000 and 25,000 cfs year round, this alternative would: (1) delay parties only at Horn Creek; (2) provide more time at attraction sites than some alternatives, yet less than others; and (3) provide a mid-range level of encounters.

ALTERNATIVE 4. In this alternative, releases from September through May would be 1,000 to 31,500 cfs, and releases from June through August would be constant at 25,000 cfs. The May scenario under this alternative was the least acceptable of all alternatives studied, producing more delays at rapids and slower river travel than any other. It would necessitate the greatest schedule changes on the part of river trips, more so than any other alternative studied. In contrast to the May scenario, the simulated summertime releases of 25,000 cfs involved no delays at rapids and provided the most time for attraction site visits. At the same time it produced a slightly higher rate of encounters.

ALTERNATIVE 5. This alternative proposes fluctuating releases from November to April between 6,000 and 10,000 cfs; in April, May, September, and October between 1,000 and 31,500 cfs; and from June through August between 3,000 and 31,500 cfs. Releases down to 1,000 cfs had the greatest effects on river trips simulated by this model. Delays at rapids combined with slow river travel reduced attraction site visit time significantly. Also, safety could be compromised by running rapids at dangerous flows in order maintain schedules.

If fewest delays at rapids, most time at attraction sites, and least encounters with other parties are the objectives with which these alternatives are evaluated, then alternatives with high releases are preferred over those with low releases, fluctuations in the high range over fluctuations in the low range, and constant releases over fluctuating releases. Therefore, none of the scenarios are optimal for river recreation. The summer months of Alternative 4 best meet the above criteria; however, the non-summer months of the same alternative are not desirable. Alternative 3, with fluctuations between 8,000 and 25,000 cfs, would be preferable to the non-summer months of Alternative 4. Alternative 1, which would baseload the dam year round, would be next, then Alternative 5, with Alternative 2 being the least preferable.

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AN ANALYSIS OF RECORDED COLORADO RIVER BOATING ACCIDENTS IN GLEN CANYON FOR 1980, 1982, 1984, AND IN GRAND CANYON FOR 1981 THROUGH 1983

This study of recorded boating accidents which occurred on the Colorado River in two National Park Service (NPS) areas below Glen Canyon Dam and above Lake Mead was undertaken to determine if a significant correlation existed between accident occurrence and river flow level at the time and location of each accident.

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INTRODUCTION

Over the last 15 to 20 years, the section of the Colorado River between Glen Canyon Dam (which forms Lake Powell) and Pierce Ferry, Arizona (on Lake Mead), a distance of approximately 300 river miles, has been heavily used for recreational boating. River flow volumes in this reach of the Colorado are controlled by Glen Canyon Dam and typically fluctuate on a daily basis in response to the level of hydroelectric power generation at the dam. Since recreational boaters on this stretch of the Colorado are regularly exposed to varying flow levels as a result of dam operations, it became desirable to determine if a correlation existed between flow level and boating accident occurrence.

The study area, a distance of approximately 240 river miles, was located between Glen Canyon Dam, in Glen Canyon, and Diamond Creek, in Grand Canyon. This area was broken down by administrative jurisdiction into the Glen Canyon National Recreation Area (Glen Canyon) section and the Grand Canyon National Park (Grand Canyon) section. Because of the marked differences in the nature of boating use and associated accidents between the sections, the accident populations for each study section were analyzed separately.

The 17-mile, non-whitewater Glen Canyon section was located between the dam and the confluence of the Paria River with the Colorado, about one mile downstream of Lees Ferry. The whitewater Grand Canyon section covered approximately 225 river miles between Lees Ferry and Diamond Creek.

The time periods for each study section, the calendar years 1980, 1982, and 1984 for Glen Canyon and 1981 through 1983 for Grand Canyon, were chosen for their diversity of flows, the number of accidents recorded, and the records available on total boating use.

METHODS

GLEN CANYON. Three sources of data were used in the study of Glen Canyon boating accidents: (1) accident reports compiled by NPS personnel on both U.S. Coast Guard and NPS forms, (2) daily and annual total boat populations on the river during the study period (compiled from Glen Canyon ranger reports), and (3) hourly flow releases at the dam for each of the 1,000 days in the Glen Canyon study period, supplied by the Bureau of Reclamation (BOR) office in Salt Lake City. There were no Glen Canyon boating records for 95 days during the study period, a time period when there were no recorded accidents, and hence this period was not included in the study.

GRAND CANYON. The study of Grand Canyon boating accidents used four sources of data: (1) accident reports compiled on standard NPS Case Incident Record, (2) river trip checkout sheets completed at Lees Ferry by Grand Canyon personnel for each of the 2,281 separate trips launched during the study period, (3) hourly dam releases for each of the 1095 days of the Grand Canyon study period, and (4) hourly computer flow routings for Grand Canyon.

BOATING ACCIDENT REPORTS. Boating accidents were defined as those river incidents resulting in notable equipment damage or loss, and/or personal injury requiring medical attention, while on the river and recorded on NPS Case Incident or Coast Guard accident report forms. All accident reports used in the study contained information on the date, time, and location of the accident. These three variables were the minimum required to determine a flow for the time and location of the accident. Any reports which lacked this information could not be included in the analysis for association with flow.

BOAT POPULATIONS. The boat population of the Glen Canyon section was almost entirely composed of hard-shelled motorboats. Boat counts made by Lees Ferry rangers on their daily Visitation Logs produced the daily, annual, and study period Glen Canyon boating population.

The Grand Canyon boat population was composed of five boat types: motor, oar, and paddle rafts; dories; and kayaks. Totals for each boat type were determined from river trip checkout sheets for the study period.

FLOW FIGURES. Flow data used in the analysis of Glen Canyon accidents consisted of hourly dam releases for each day of the Glen Canyon study period. These releases represented the flow values used for both the accident and non-accident Glen Canyon boat populations. The average speed of flow in the Glen Canyon section is approximately 4 to 5 miles per hour. The flow at each accident location was calculated by dividing the river mile location of the accident by 4.5 and then subtracting that figure (in hours) from the time of the accident. The dam release at the resulting time was used as the flow for that accident.

For each Grand Canyon accident, BOR provided flow data in the form of a flow routing for the day of the accident. These flow routings consisted of measured and estimated hourly flows at twelve locations within Grand Canyon (starting at Lees Ferry and ending at Diamond Creek) and were generated by BOR's computerized Streamflow Synthesis and Reservoir Regulation (SSARR) Colorado River flow model. The flows at the time and place of each Grand Canyon accident could then be determined using these routings.

For this analysis, river flows (measured in cubic feet per second [cfs]) were divided into four flow range categories: Low, < 9,000 cfs; Medium, 9,000-15,999 cfs; High, 16,000-31,500 cfs; and Flood, > 31,500 cfs.

DATA ANALYSIS. For both the Glen Canyon and Grand Canyon sections of the river, it was necessary to determine what percent of the time boats were subjected to each of the four flow range categories (which we called boat-hours per flow range, or simply boat-hours). Statistically similar distributions of accident occurrence and boat-hours would indicate a random distribution of accidents within the flow ranges, conversely a non-random distribution would indicate that some factor, possibly flow, was associated with accident occurrence. The non-parametric Chi-Square Test for Association was used to test for a flow-accident relationship because of the very low (0.5 percent or less) accident rate for both study sections.

For Glen Canyon, total boat-hours per flow range was computed by: (1) manually categorizing daylight hourly dam releases into each flow range and entering daily totals into the computer; (2) using ranger-supplied daily boat counts for each day of the study period and entering daily totals into the computer; and (3) multiplying the number of boats on the river each day by the total daily hours per flow range.

For Grand Canyon, the NPS river use data file, giving launch date, boat numbers and types, and takeout date (at Diamond Creek) was computerized and used as the source for the number of boats on the river each day. To compute boat-hours per flow range, we needed to determine the dam releases which boats experienced. This was much more difficult for Grand Canyon than for Glen Canyon for four reasons: (1) dam releases take upwards of two days to reach Diamond Creek; (2) there is attenuation of river flow downstream of the dam; (3) even though trips are on the river only during daylight hours, both daytime and nighttime dam releases are experienced by boaters somewhere along the river; and (4) it was not possible to determine precisely where any particular boat was at any particular time after launching from Lees Ferry, precluding the use of the SSARR flow model to match boats with flows. Therefore, all 24 hours of dam releases were used for each day that trips were on the river. Although this method is not precise, it consistently produced a reliable proportion of boat-hours in each flow range per day based on the number of boats on the water.

To compute total boat-hours for the Grand Canyon section, the number of boats on the river each day was multiplied by the total daily boat-hours per flow range.

Chi-Square analysis of the accident distribution required converting the percentage of total boat-hours in each flow range to whole numbers representing expected accidents. This was accomplished by multiplying the total boat-hours percentage in a given range by the total number of study period accidents. The distributions of recorded and expected accidents could then be statistically compared.

RESULTS AND DISCUSSION

GLEN CANYON. Applying the Chi-Square Test For Association to the recorded vs. expected accident distributions for the entire 3-year study period in Glen Canyon showed the recorded accident distribution by flow range to be non-random ($X = 10.967$, $df = 3$, $P < 0.05$) (Table 1). Almost twice the expected number of accidents occurred in the High flow range (recorded: 20.00, expected: 11.55) and less than a third of expected accidents occurred during the Medium flow range (recorded: 2.00, expected: 7.19) (Figure 1).

Table 1. Percent of total Glen Canyon boating accidents vs. percent of total boat-hours in each flow range, and recorded vs. expected Glen Canyon boating accidents by flow range for 1980, 1982, and 1984.

	Flow Range			
	Low	Medium	High	Flood
Percent of total Glen Canyon accidents	20.69	6.90	68.96	3.45
Percent of total boat-hours in each flow range	30.00	24.79	39.83	5.38
Recorded accidents	6.00	2.00	20.00	1.00
Expected accidents	8.70	7.19	11.55	1.56

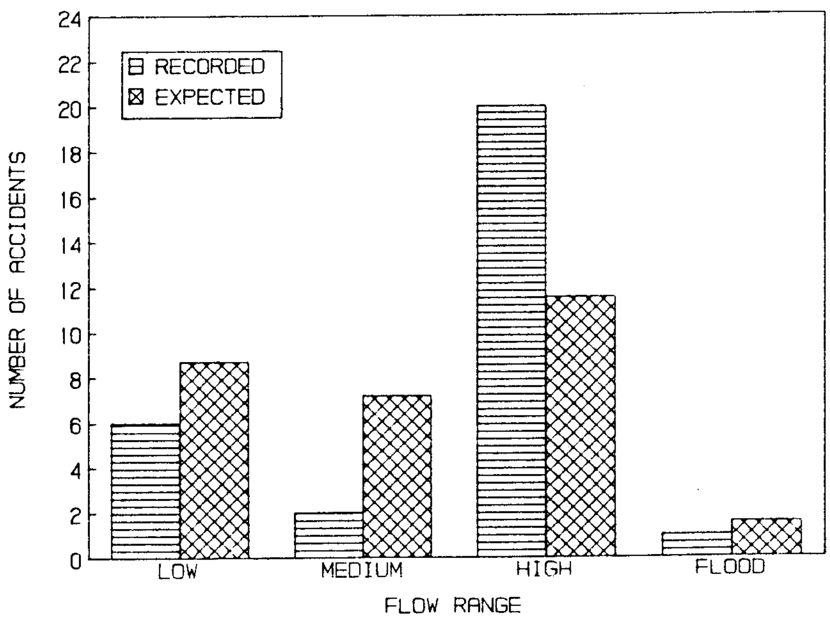

Figure 1. Recorded vs. expected Glen Canyon boating accidents by flow range for 1980, 1982, and 1984.

Analysis of the annual Glen Canyon accident distributions indicated that each year was random (all P's > 0.05). This result, however, may have been caused by the small number of annual accidents.

Although it would be desirable to assume that the other non-flow related variables (operator experience, wind, boat or motor condition, etc.) remained constant across flow ranges, this was not possible for two reasons: (1) the post-hoc, correlational design of the study does not allow for such an assumption; and (2) it was impossible to attain a random sample or to randomly assign events to groups. While the availability and consistency of these data were insufficient to support a statistical analysis, enough information was contained in all of the Glen Canyon reports to warrant a descriptive analysis.

The descriptive analysis revealed that high winds were reported at the time and place of 9 of the 29 Glen Canyon accidents, although only 7 accident reports indicated that high winds may have contributed to the accident. The river surface was recorded as being rough or very rough for these same nine accidents.

Strong river current was reported for 17 accidents. Our analysis has shown that 20 accidents occurred during high flows and one during flood flows. Water conditions were characterized as being rough, very rough, or having strong current in 19 of the accident reports. However, only 12 reports specifically indicated that these water conditions may have contributed to accident occurrence. The combination of bad weather (cloudy, rain), high winds, and rough water/strong current occurred in four reports.

Descriptive analyses of boat-related variables revealed that four accidents were considered to have been at least partially caused by overloading or improper weight distribution. One of these resulted in two fatalities, the only deaths reported during the study period. Equipment failure was indicated as having contributed to or have been the principal cause of nine accidents. Strong current or rough water was also cited as a major contributing factor in eight of these nine accidents.

Operator error was listed as a probable cause in 11 accidents. This error involved bad judgment and/or carelessness in boat operation. Examples included producing boat-swamping wakes and in two instances anchor dragging from the bow.

Analysis of overall Glen Canyon accident occurrence by location revealed that eight accidents occurred on the mile of river between Lees Ferry and the Paria/Colorado confluence, six occurred 3.0 to 3.5 miles upstream of the Ferry, and two each occurred 5.5 miles, 9.0 miles, and 12.0 miles upstream of Lees Ferry.

Six of the eight accidents associated with equipment failure and strong current/rough water occurred between Lees Ferry and the Paria confluence. Seven of the nine total equipment failure related accidents occurred in this section of the river. All nine high wind related accidents occurred between three and twelve miles upstream of Lees Ferry, with four of these occurring in the 3.0- to 3.5-mile area.

The overall non-random distribution of accidents appears to result from the considerably lower than expected number of accidents which occurred in the Medium flow range and the considerably higher than expected number which occurred in the High flow range. A possible interpretation of this distribution is that boaters were much more likely to have problems that resulted in accidents during high (but not flood) flows and much less likely to get into accident producing situations during medium and low flows.

During the three years of this study, 27,747 boat-days were reported to have occurred on the Glen Canyon section of the Colorado River, with 29 being involved in a recorded boating accident on the river. The overall accident rate per boat-day is 0.104 percent, which translates to one recorded accident for every 957 boat-days on this section of the river (Table 2). How this rate compares to other American rivers with similar recreational boating use is not known.

Table 2. Annual boating use and number of boating accidents in Glen Canyon for 1980, 1982, and 1984.

	Year			
	1980	1982	1984	Total
Total reported boat-days	5,548	14,442	7,757	27,747
Recorded boating accidents	8	8	13	29
Accident rate	0.144% (1:694)	0.055% (1:1805)	0.168% (1:597)	0.104% (1:957)

GRAND CANYON. Chi-Square analysis of the recorded vs. expected accident distributions for the complete study period in Grand Canyon showed the recorded accident distribution by flow range to be random (X = 5.206, df = 3, $P < 0.05$) (Table 3). Analysis of the annual Grand Canyon accident distributions indicated a random distribution for each year (all P's > 0.05) (Figure 2).

Table 3. Percent of total Grand Canyon boating accidents vs. percent of total boat-hours in each flow range, and recorded vs. expected Grand Canyon boating accidents by flow range for 1981 through 1983.

	Flow Range			
	Low	Medium	High	Flood
Percent of total Grand Canyon accidents	22.50	35.00	25.00	17.50
Percent of total boat-hours in each flow range	28.87	25.01	35.53	10.59
Recorded accidents	9.00	14.00	10.00	7.00
Expected accidents	11.56	10.00	14.20	4.24

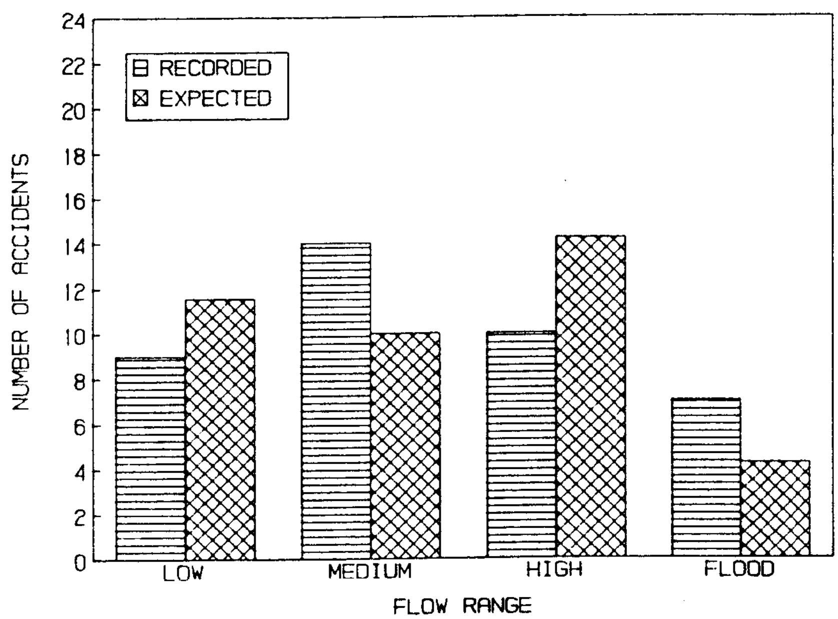

Figure 2. Recorded vs. expected Grand Canyon boating accidents by flow range for 1981, 1982, and 1983.

Analysis of the distributions of recorded vs. expected accidents with respect to boat type (motor, oar, and paddle rafts; dories; and kayaks) and flow range in Grand Canyon showed them all to be random. All five types had similar exposures to each flow range during the study period.

Location was also analyzed as a factor in Grand Canyon boat accidents. A total of 40 accidents were recorded for the three-year study period (13 each in 1981 and 1982, and 14 in 1983) at 20 rapids. Crystal and Badger Creek were the only rapids where accidents were recorded in each of the three years. Twenty-five of the 40 accidents occurred in five locations: Badger Creek (river mile [RM] 8) = 3, Grapevine (RM 82) = 3, Horn Creek (RM 90) = 5, Crystal (RM 98) = 11, and Lava Falls (RM 179) = 3.

The distribution by flow was similar for 1981 and 1982, with almost all of the 13 accidents for each year occurring in the Low and Medium ranges. The 1983 distribution was markedly different from that in 1981 and 1982, with all 14 accidents equally distributed in the High and Flood ranges. 1983 had post-dam record high flows (> 92,000 cfs) during the peak rafting season (May - September) while both 1981 and 1982 had fluctuating flows during this period when most (75 percent) of the annual boating use in Grand Canyon occurs.

In an effort to determine possible influences on accident occurrence with respect to flow and location, several location characteristics for which data were available were examined. These included dominant geologic strata, channel type, vertical drop, navigational difficulty rating, and boat type.

Of the five major accident locations (Badger Creek, Grapevine, Horn Creek, Crystal, and Lava Falls), all except Badger are geologically composed of igneous-metamorphic or volcanic strata. Badger accounted for only three of the 25 accidents occurring at these five rapids. Therefore, 22 (88 percent) of these accidents occurred in rapids formed by non-sedimentary strata. Overall, 30 of the 40 recorded Grand Canyon accidents occurred in rapids formed in non-sedimentary strata.

The navigational difficulty assigned to Grand Canyon rapids is based on the Western (or American) scale of river rapid rating. This scale ranges from 1 to 10 with a rating of 1 indicating an easily run rapid and 10 indicating an extremely difficult and dangerous (sometimes unrunnable) rapid. The ratings are made largely from the perspective of oar-powered boats (Interagency, 1980; Stevens, 1983). The average navigational difficulty was 9 for the five major accident locations, and about 6 for the other 15 locations.

Relating flow level to the five major accident locations provides perhaps the most interesting combination of known accident variables. Each location is discussed separately. Chi-Square analysis of the recorded accident distribution by flow range for Crystal Rapid showed it to be non-random ($X = 15.338$, $df = 3$, $P < 0.05$). In order to compute expected accident values for each of the five major Grand Canyon locations, boat-hours per flow range were needed for all boats passing through each rapid. Due to difficulties discussed earlier, an assumption had to be made that the flows at the rapid were the same as those released at Glen Canyon Dam. This premise is not entirely accurate because of attenuation and temporal delay of flows through the canyon. However, it was necessary due to the inability of pinpointing boat locations at any given time, and it did provide a consistent method for computing boat-hours.

All 11 recorded Crystal Rapid accidents involved only motor and oar rafts. The analysis of these accidents by boat type showed a non-random distribution of motor raft accidents among the flow ranges ($X = 16.052$, $df = 3$, $P < 0.05$) and a random distribution for oar raft accidents ($X = 1.142$, $df = 3$, $P > 0.05$). Five of the seven motor raft accidents at Crystal occurred during Flood flows, while Crystal oar raft accidents were fairly evenly distributed among the flow ranges.

Testing Crystal Rapid accidents as a group for possible association between boat type and flow showed an association between these variables ($X = 8.130$, $df = 3$, $P < 0.05$). The association appears to have been primarily the result of the high number of motor raft accidents in the Flood flow range. Five of the 11 Crystal accidents occurred during the 1983 spills. All five accidents involved large motor rafts and occurred at flows between 61,200 and 70,500 cfs during one week in June. There were considerable equipment losses and damage, many injuries, and one fatality.

While Crystal Rapid was a problem for motor rigs at flood flows, Horn Creek Rapid appears to have been most dangerous during low and medium flows. All five accidents there occurred in flows between 7,000 and 10,850 cfs. Note that this spread involves both the Low and Medium flow ranges.

With only five accidents occurring in two flow ranges, applying Chi-Square analysis to Horn Creek Rapid accidents would not have been statistically valid, and therefore was not done. However, the grouping of all five accidents (involving motor, oar, and paddle rafts) in flows between 7,000 and 10,850 cfs strongly suggests that Horn Creek is most dangerous below 11,000 cfs for all boat types. Horn Creek is considered by experienced river runners to be most dangerous between 4,000 and 10,000 cfs (Stevens, 1983).

Badger Creek, Grapevine, and Lava Falls Rapids each had three recorded accidents during the study period, too small a number on which to draw conclusions. The circumstances of accident occurrence at each location may, however, provide useful information.

Two of the three Badger Creek Rapid accidents occurred between 6,000 and 7,000 cfs, the other at 28,200 cfs. All three Grapevine Rapid accidents occurred in the High flow range, between 22,600 and 27,900 cfs during the summer of 1983. Two occurred at 27,900 cfs, and all three involved rafts (two motor, one oar). Like Horn Creek, it would appear that Grapevine is most dangerous within a narrow band of flows, in this case in the High range.

The three recorded Lava Falls Rapid accidents all occurred in the Medium flow range (9,100 to 12,750 cfs) during the summer of 1982. Two of the three accidents involved oar rafts. These circumstances suggest that Lava Falls was most dangerous in Medium range flows during the study period.

Analysis of the channel type variable revealed that there is a similar distribution between straight channel alignments and those on a bend (22 vs. 17) among all locations.

Vertical drop figures indicate that there is an average drop of 18' for the five major accident locations, and slightly greater than 14' for the 15 individual accident locations. This may in part explain the difference in the average difficulty rating for the two location groups. Vertical drops, as well as some other variables, were not available for some locations.

SUMMARY STATISTICS. During the three years of this study, 7,727 boats were launched from Lees Ferry in 2,281 separate trips, resulting in over 75,000 boat-days on the river. During this time period, the NPS recorded 40 accidents which occurred while navigating the river. The overall per boat accident rate was 0.52 percent, which translates to one of every 193 boats launched from Lees Ferry being involved in a recorded accident (Table 4). The per boat-day rate is 0.05 percent, and the per trip rate was 1.75 percent, with one trip in 57 having a recorded accident.

Table 4. Total boating population vs. accident population by boat

	Oar	Motor	Kayak	Dory	Paddle	Totals
Total population	3,685	2,172	1,353	343	174	7,727
Accident population	14	21	1	3	1	40
Accident rate	0.38% (1:263)	0.97% (1:103)	0.074% (1:1353)	0.88% (1:114)	0.58% (1:174)	0.52% (1:193)

Comparing the population sizes and accident rates of each boat type showed that motor rafts, with 2,172 total boats, had the highest accident rate. This rate was almost three times greater than the rate for oar rafts. Oar and motor rafts combined accounted for 76 percent of the total boats and 88 percent of the total recorded accidents. Dories, with the second lowest number of boats, 343, had the second highest accident rate. Kayaks had the lowest accident rate. Although there are wide variations among the boat types, it is important to remember that the overall accident rate is still less than one percent.

CONCLUSIONS

The results of this analysis indicate that there is no statistical association between flow and recorded boating accident occurrence on the Colorado River in Grand Canyon National Park during the years of 1981 through 1983. However, certain accident locations do show association between flow and accident occurrence. Crystal Rapid between 60,000 and 70,000 cfs and Horn Creek Rapid below 11,000 cfs are the best examples.

The overall accident rate is low and data on other accident related variables, such as operator experience and weather conditions, are lacking. Under these circumstances, it is very possible that variables other than flow may have significant impacts on accident occurrence. Without data on these associated variables, it is difficult to assess the relative effect of one or two.

The analysis of data for this study and discussions with informed sources strongly suggests that many more accidents occur than are actually recorded by the NPS in both study sections. This situation may provide impetus for additional boating accident research.

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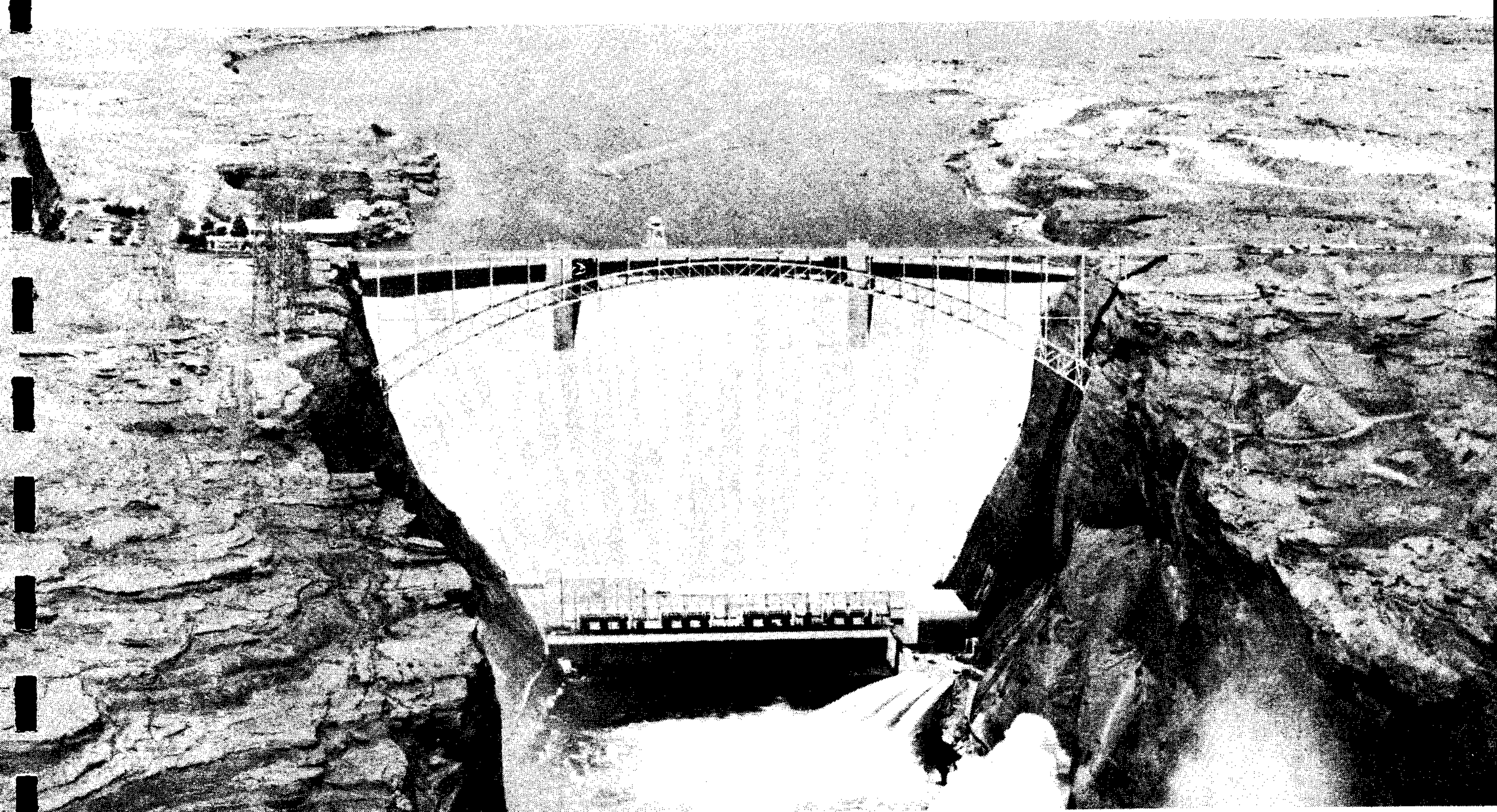
Section VI: Dam Operation Information



SECTION VI: DAM OPERATION INFORMATION

COLORADO RIVER STORAGE PROJECT CONSTRAINTS AND THE OPERATION OF GLEN CANYON DAM, ARIZONA

The release of water from Glen Canyon Dam to Glen and Grand Canyons is controlled by a combination of physical, legal, and system boundaries and interpretations. The information presented in this report outlines the major parameters that are considered in the determination of the actual releases that occur at Glen Canyon Dam.

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INTRODUCTION

The Colorado River winds over 1,400 miles through seven western states and northern Mexico and collects water from over 244,000 square miles. It is the primary source of water for the basin. The economic health, recreational opportunities, and growth potential of many communities in the Colorado River Basin are directly related to the management of the river.

Glen Canyon Dam is the key water regulatory feature on the Colorado River. The objective of this report is to outline the constraints and criteria that define the operation and management of Glen Canyon Dam and to describe the operation of the dam as related to the management of the Colorado River system, The Colorado River Storage Project (CRSP) Act, the Western Area Power Administration (WAPA) power and transmission system, and the consultation process with the Colorado River Basin states. The Department of the Interior, with its Secretary, has the responsibility in the Colorado River system to ensure that each state receives its defined allocation. The actions of the Department of the Interior are set within the defined legal, river system, and physical constraints of the Colorado River basin.

The information presented in this report provides background on the operation and management of Glen Canyon Dam. This report is <u>not</u> presented as an in-depth description of all the legal and political balanacing that defines the operation of the dam. RAther, it outlines the operational framework and boundaries that are taken into account in the determination of the managment of Glen Canyon Dam and consequently the releases into the Glen and Grand Canyons.

GLEN CANYON DAM MANAGMENT FRAMEWORK

The scarcity and unpredictable nature of water in the Colorado River Basin have resulted in a long history of competition for the limited water resources. Over the past 100 years, uses of the Colorado River have increased exponentially and demands on it have accelerated.

Today, over two million acres of agricultural land are irrigated in the Colorado River basin. Reservoir storage capacity totals over 61.5 million acre-feet (maf) and can provide over 3,330,000 kilowatts of electrical capacity. Given the importance of the Colorado River and the demands made upon it, it has been necessary to physically and legally control use of the river. The legal control has been defined through a number of Congressional acts, court decisions, treaties, and compacts known collectively as the "Law of the River" (Nathanson 1978).

Wise management of the Colorado River Basin was argued for by John Wesley Powell (1962) as early as 1878. His arguments were largely ignored. E.C. LaRue (1916) followed Powell's philosophy and identified the necessity for a comprehensive water supply study of the entire Colorado River Basin. During the early 1920s, the seven Colorado River Basin states (Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming) realized that control of the Colorado River required a coordinated approach. The need to control storage and available water supplies led to the negotiation of the 1922 Colorado River Compact (Compact) (Olson 1962). This first interstate water compact was intended to balance the expanding demands of the Lower Basin states and the need to preserve adequate water for future use in the less-developed Upper Basin states.

The Compact officially divides the Colorado River Basin into the Upper and Lower Basins. The dividing point, or Compact Point, was established at Lees Ferry, Arizona. The Compact apportions, in perpetuity, 7.5 maf of Colorado River water annually to each basin. In addition, the Lower Basin was given the right to increase its apportionment by as much as 1.0 maf in any given year. The Compact required Upper Basin delivery of 75.0 maf for any period of ten consecutive years to the Lower Basin.

The Compact was the first step to legally define the Colorado River rights of the seven basin states, but it was by no means the last. Additional laws, treaties, and court decisions continue to refine the interpretation and allocation of Colorado River water. The composite of all of these actions define the "Law of the River." The primary actions are listed in Table 1 and are more fully discussed in Weatherford and Brown (1986) and Nathanson (1978).

Table 1. Primary Colorado River laws and interpretations.

Colorado River Compact (signed)	November 24, 1922
California Limitations Act	March 4, 1929
Boulder Canyon Project Act (45 Stat. 1057) (signed)	June 25, 1929
Arizona v. California	1931, 1934, 1936
Mexican Water Treaty (Treaty Series 994)	November 8, 1945
Upper Colorado River Basin Compact	October 11, 1948
Colorado River Storage Project Act (70 Stat. 105)	April 11, 1956
Arizona v. California (373, U.S. 564, 565 [1963])	March 9, 1964
Colorado River Basin Project Act (P.L. 90-537)	September 30, 1968
Colorado River Basin Salinity Control Act (Minute No. 242)	August 30, 1973

While all of the define laws, treaties, and legal interpretations impact the allocation of the Colorado River, the CRSP Act specifically allowed for the construction of Glen Canyon Dam.

<u>Colorado River Storage Project Act.</u> The CRSP Act (70 Stat. 105) passed on April 11, 1956, provides for the comprehensive development of the water resources of the Upper Colorado River Basin and long-term regulatory storage of Colorado River water to meet the commitments of the Colorado River Compact (Upper Colorado River Commission 1987).

Originally, the CRSP plan included ten dams and reservoirs within the Upper Colorado River Basin. Six dams were finally authorized for construction (Meyers 1967).

The primary objectives of the storage projects were to regulate the flow of the Colorado River, to store water for beneficial consumptive use, to provide reclamation of arid and semiarid land, to provide control of floods, and as an incidental basis to generate hydroelectric power (U.S. Department of the Interior 1954). The revenues generated by the project would be used to repay the cost of construction and operation and maintenance requirements.

The hydroelectric powerplants and transmission lines authorized by the CRSP Act are directed to operate in conjunction with other Federal powerplants and to produce the greatest practicable amount of power. The revenues collected from the generated power are to repay the initial government investment of the CRSP dams and provide support for other Bureau of Reclamation (BOR) participating projects.

Construction of Glen Canyon Dam began in 1956 and was completed in 1963. The structure impounds Lake Powell, a 27 maf reservoir with Glen Canyon Dam being the key regulatory element controlling water releases to the Lower Basin.

LEGAL OPERATING CRITERIA OF GLEN CANYON DAM

The operation of Glen Canyon Dam is controlled by the physical parameters of reservoir size, annual runoff, discharge capacity, the legal and institutuional constraints specified by Federal laws, an interstate compact, an international treaty, and Supreme Court decisions.

The legal mandates that are important to the management of the Colorado River and Glen Canyon Dam are listed in Table 1. Specific legislative accords that direct actual dam operation include the Filling and Operating Criteria for Glen Canyon Dam. The **Filling Criteria** for Lake Powell had three main objectives: (1) to provide sufficient water to meet 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 at the earliest feasible time. Elevation 3,490 feet is the minimum elevation necessary to initiate power generation. Specific managment principles were establsihed to assist in the achievement of these objectives. The Filling Criteria were approved in April 1962 by Secretary of the Interior Stewart Udall and were terminated in June 1980 when Lake Powell reached the full reservoir elevation of 3700 feet.

The **Operating Criteria** for Glen Canyon Dam were adopted in 1968 as part of the Colorado River Basin Project Act (Section 602(b) of P.L. 90-537) to cover the coordinated long-range operations of facilities of the CRSP, Parker-Davis Project, Boulder Canyon Project, and the participating CRSP projects.

Section 602(a) of the Operating Criteria requires the Secretary of the Interior to prepare an annual report that describes the actual operations of the Colorado River reservoirs under the 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 delivery requirements. The actual amount of 602(a) storage required in Lake Powell to meet the Lower Basin states requrements has not been determined by the Secretary. If too little water is in Lake Powell storage, releases from Glen Canyon Dam will be limited to 8.23 maf. However, if excess water exists, releases greater than 8.23 maf can be made to accomplish specific goals defined in the Act. These goals include fulfilling the requirements of the Colorado River Compact as related to deliveries to the Lower Basin states and the requirements of the treaty with the country of Mexico.

The objective of the Operating Criteria was a more efficient and reasonable river management. The Operating Criteria take into consideration the great diversity among the Colorado River system users and stipulate that any plan of operation must reflect appropriate consideration of the uses of the reservoirs for all purposes including flood control, water quality control, recreation, enhancement of fish and wildlife, and other environmental factors.

The Secretary of the Interior may modify the Operating Criteria. A formal review of the Operating Criteria is made at least every five years, with participation by state representatives and others that the Secretary may deem appropriate. In addition, each year the Colorado River Basin states and the Secretary agree on an Annual Operation Plan (AOP) for the reservoirs of the Colorado River.

Operation of the Upper Basin Reservoirs. The operation of the Upper Basin reservoirs takes into account many factors with the overall objective being to ensure an annual release of water to the Lower Basin states of 8.23 maf. Lake Powell is the primary "water bank" from which the releases are made. If the Upper Basin storage reservoirs' active storage forcast on 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 from Lake Powell at a rate greater than 8.23 maf.

Objectives of this additional release include: to reasonably serve beneficial domestic and agricultural needs; maintain, as nearly as practical, equal active storage in Lake Mead and Lake Powell; and avoid bypassing water.

HISTORIC OPERATION OF GLEN CANYON DAM

Management of Glen Canyon Dam has had an impact on the flow patterns of the Colorado River through the Glen and Grand Canyons. Three distinct phases of river flow can be interpreted from the flow records.

Phase I. Pre-dam, 1922-1962. The pre-dam period was characterized by frequent, natural, high flows in the late spring and early summer seasons and by low flows during the late summer, fall, and winter seasons. Mean daily flows in excess of 80,000 cubic feet per second (cfs) were common and occasionally reached the 100,000 cfs level. 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. Variability in flow occurred on a seasonal basis.

Phase II. Lake Powell Filling, 1963-1980. Lake Powell began storing water in March 1963, and was filled in June 1980. The management of Lake Powell and the operation of Glen Canyon Dam was accomplished under the Filling Criteria to ensure the efficient and timely filling of Lake Powell and to minimize the impact to the downstream operation of Hoover Dam.

Little water was released for the first two years following Glen Canyon Dam closure. In 1965, Lake Powell achieved the minimum elevation necessary for power production (3490 feet). However, the elevation of Lake Mead dropped below the minimum necessary for operation of the Hoover Powerplant. This shortage of water occurred prior to spring runoff being available to supplement water volumes necessary to meet the downstream water use requirements. Subsequently, nearly 11 maf of water was released prior to the spring runoff in 1965 from Lake Powell to restore the minimum reservoir elevation at Lake Mead. Releases from Glen Canyon Dam were targeted to achieve the 75 maf for any period of ten consecutive years as legislated by the Colorado River Compact.

The Operating Criteria were implemented prior to the termination of the Filling Criteria in order to provide a more efficient management of the Colorado River System. 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. Variability in flows changed from a seasonal basis to a daily basis.

<u>Phase III. Lake Powell, Post-filling, 1981-Present.</u> The post-filling period of Lake Powell and the operation of Glen Canyon Dam has been characterized by the preponderance of high flow releases. The 1984 inflow to Lake Powell was the highest of record and the 1983 inflow was the third highest of record. Since releases from Glen Canyon Dam in four of the last six years have been unusually high, the releases have been 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 92,500 cfs. Even with the data bias, only approximately 10 percent of the flows of the period were greater than 25,000 cfs.

CURRENT OPERATION OF GLEN CANYON DAM

Flows through Glen and Grand Canyons are influenced by storage and release decisions that are made and scheduled annually, monthly, and hourly from Glen Canyon Dam. The annual decisions are in conformance with the legal mandates and Operating Criteria.

The monthly decisions are generally intermediate targets determined as necessary to systematically achieve the annual requirements. The hourly schedules are set to meet the monthly volume targets but are primarily influenced by the power demands and minimum flow requirements. BOR sets the annual and monthly release volumes and WAPA determines the daily and hourly actual release levels.

Determination of Annual Release Volumes. Release schedules vary greatly in annual release volumes, but each adheres to the minimum release of 8.23 maf and equalization of storage between Lake Powell and Lake Mead. Annual releases greater than the minimum of 8.23 maf are permitted only 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, or if runoff volumes cannot be stored in Lake Powell.

As a practical matter, the reservoir is targeted to fill each July. An informal understanding between BOR and the Upper Basin states established an annual January 1 volume target for Lake Powell storage at 22.6 maf as an intermediate target and to achieve full reservoir conditions (27 maf) by 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. Negotiation between BOR and the Upper Colorado River Basin states are on-going to determine if a lower reservoir limit could be set that would still allow enough flexibility to meet the legal release requirements.

Since there has not been a numerical determination of actual 602(a) storage (the amount of water actually required in the Lower Colorado River Basin), a practical solution has been to keep Lake Powell full. In addition, since 1983, releases in excess of 8.23 maf annually have been allowed only under the Criteria provision of avoiding spills. Excess water is released only to the extent required by the forecast to avoid powerplant bypasses. This practice has also contributed to keeping Lake Powell full.

Determination of Monthly Release Volumes. Operational flexibility is greatest when the monthly release volumes are moderate and least when monthly release volumes are low or high. Monthly release volumes greater than 1,200,000 acre-feet (af) require hourly and daily rates to be near maximum powerplant capacity in order to pass the monthly volume downstream. Monthly volumes between 600,000 and 1,200,000 af allow more flexibility from the power production point of view. Monthly releases less than 600,000 af do not have enough flexibility to take advantage of the entire peaking capability, maintain the minimum release rates, and conform to the monthly volume requirements. Typical 1983-1986 operations involved running the powerplant at, or near, full capacity 24 hours a day.

Fall and winter releases are managed to meet the January 1 storage target. January through March releases are managed to develop space in Lake Powell to accommodate forecasted Upper Basin runoff. April, May, and June releases are managed to accommodate the changes in inflow as they occur and to achieve a full reservoir 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.

After all these considerations and monthly volumes have been satisfied, then seasonal variations in the power demand are considered. Power needs are highest during the coldest winter and hottest summer months. Therefore, higher releases are scheduled in these months whenever possible.

Determination of Hourly Release Volumes. Hourly releases from Glen Canyon Dam are generally set to achieve programmed monthly release volumes, to maintain established minimum rates, and to follow the pattern of energy demand. The physical limitations of the powerplant and the minimum flow requirements define the boundaries of the power releases.

The agreed upon minimum flow requirements are: 3,000 cfs from Easter Sunday to Labor Day with a daily on-peak (8:00 am to 11:00 pm) average of 8,000 cfs; and 1,000 cfs from Labor Day to Easter Sunday (U.S. Bureau of Reclamation 1988).

The following guidelines are followed, to the extent possible, within the higher priority operation 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 7:00 am and 11:00 pm; (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 generator units.

Demand for power may change the rate at which water is released; however, this demand is not supposed to alter the releases required to satisfy other project purposes. Emergencies may cause severe departures from expected schedules, but these emergencies are usually of short duration and their effect on release volumes can be mitigated rapidly.

<u>Glen Canyon Dam Uprate and Rewind Program.</u> In 1975, an inspection of Glen Canyon Dam generators revealed that the original generator windings were reaching the end of their service life and that a "rewinding" of the eight generators was necessary to maintain efficient operation.

A decision to "uprate" the generators at Glen Canyon Dam was made to reduce power generation constraints and to provide for more efficient use of the other power system components.

Because uprating is not a normal maintenance function, compliance with the National Environmental Policy Act (NEPA) was required. An environmental assessment, completed in 1982, resulted in a Finding of No Significant Impact (UC-FONSI 83-1) (U.S. Bureau of Reclamation 1982). The uprating of the eight generators at Glen Canyon Dam began in 1983. Before uprating, the maximum release ranged from 27,500 to 31,500 cfs, depending on lake elevation. The elevation of the reservoir determines the head, or pressure, on the turbines which drive the generators. After generator uprating was completed in 1987, the maximum releases are now able to range from 32,200 to 33,100 cfs. However, releases are limited to 31,500 cfs until the completion of the Glen Canyon Environmental Studies.

<u>Risk of Flood Releases.</u> The ideal operating plan would enable the reservoir to fill each year without risking flood-level releases. Unfortunately, forecasted inflows have a large degree of uncertainty and variability which amplified the risks of either flood releases or not filling the reservoir.

Flood releases occur under 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 late-season increases in the inflow which exceed the available storage and release capability.

One of the key criteria for the operation of Glen Canyon Dam is to avoid releases which bypass the powerplant. Therefore, under high inflow conditions, releases are held at or near 31,500 cfs until greater releases are necessary. Due to forecast uncertainties, the decision to exceed 31,500 cfs is often delayed in the hope that actual inflow will be less than that forecasted. If the forecast is correct or even underestimates inflow, this delay necessitates releasing larger flows than would have been required had flood releases been started earlier.

COLORADO RIVER STORAGE PROJECT POWER MARKETING

In 1961, BOR initiated the development of a plan to market the hydroelectric power from the CRSP. Two components of the hydroelectric power were marketed: energy and capacity. Energy is the electrical work produced from a power generating unit of a period of time. Capacity is the load (or potential energy) for which a generator is rated. A public participation process assessed the interest in the power and developed long-term firm (will be always provided) power contracts for the future energy to be produced by the CRSP powerplants, including the yet to be completed Glen Canyon Dam.

The marketing criteria utilized in the formulation of the initial power contracts took into account the following items: (1) the source of power, (2) how much power would be available and when, (3) who would be eligible to participate and receive the power, and (4) how the power was to be delivered and where, and (5) the provisions and restrictions contained in the firm power contracts.

The Department of Energy (DOE) was formed by Congress in 1977 (P.L. 95-91) and assumed the Federal power marketing responsibilites for BOR. Western Area Power Administration (WAPA) was established as an agency within DOE to market and transmit Federal power within 15 central and western states.

WAPA operates and maintains the Federal transmission lines and substations. Power is sold by WAPA to municipalities, rural electric cooperatives, public utility districts, private utilities, Federal and state agencies, irrigation districts, and other project-use customers. It is estimated that over 15 million people can be serviced by these entities.

With the creation of WAPA and expansion of southwest regional electric needs, it was determined by WAPA that the original 1962 General Power Marketing Criteria for the CRSP hydroelectric power (promulgated by BOR) required modification. The changes were necessary to redefine the geographic market area, the availability of peaking power, and to identify additional delivery points and conditions.

A provision of the modification, completed in February 9, 1978, extended the termination date of the original power contracts to September 1989 and defined specific BOR and WAPA responsibilities. WAPA is currently in the process of developing the post-1989 marketing criteria to be used in establishing future power contracts (U.S. Department of Energy 1985).

Under a 1980 agreement between BOR and WAPA, BOR manages the reservoirs and generates hydroelectric power and WAPA markets, transmits, and regulates power delivery to the customers of the CRSP. The power generated at Glen Canyon Dam and the other CRSP powerplants is marketed by WAPA on both a long-term, firm basis through electrical sales contracts, and on a short-term basis through agreements with firm power customers or associated utilities.

Long-term Marketing. The determination of the amounts of power available for long-term marketing and the distribution of this power to utility systems is a cooperative effort between BOR and WAPA. BOR utilizes a computer model and historic hydrological data to predict available water and power resources for future time periods. The model utilizes anticipated Upper Basin water depletions, historic hydrological conditions, known reservoir storage capacity, plus known and anticipated physical resources to predict the availability of power resources. WAPA also assesses the availability of the hydroelectric resource, with consideration given to the predicted probability of occurrence of varying levels of hydroelectric resource during future periods. This assessment results in a proposed level of risk associated with a particular level of hydroelectric resource to be offered.

After the completion of the initial resource assessment, WAPA develops a formal marketing plan and establishes criteria through the public participation process. The marketing criteria provides the framework for allocation of the available hydroelectric resources and the basis for power contracts.

Within the framework of the marketing criteria, WAPA requests applications for power needs from eligible entities; prepares allocations; and negotiates and executes formal, long-term, power contracts with preferred customers. WAPA takes power generated by BOR at the CRSP facilities and delivers it to customers at agreed to Points Of Delivery in the interconnected transmission system, commonly referred to as the Western Grid.

Customers often purchase power from the CRSP system to complement other sources of electrical generation. Large thermal powerplants (coal-fired), which utilities generally operate continuously at or near maximum output (base loaded), 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 increase generation by bringing on line less-efficient interim units.

As electrical needs increase, additional thermal units, called "peaking units," are brought into use. These are generally oil- or gas-fired, and provide additional electrical needs for a relatively short period of time, at a substantially higher cost per unit of energy generated. The resources of the CRSP are commonly used to supplement this need for peaking power and displace the power generated by the less efficient, and more costly, peaking units. Glen Canyon Dam is classified as an "intermediate" load facility and provides both base and peaking capability.

During the nighttime hours, an excess of power is available and the cost for that power is substantially reduced. CRSP powerplants reduce generation at night to save the potential power resources for the peaking period.

The CRSP system is also commonly managed to "store" off-peak energy from thermal generating sources for use during peak load 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 peak load hours, the water that was stored is released and the power generated sold to displace the higher priced peaking units.

The CRSP system is also used to match minute-by-minute load changes. Hydropower 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 used as backup generation capacity in case of unexpected system outage or emergency situations.

Short-term Marketing. When the available electrical resource is greater than the defined electrical demand (firm contracts), a portion of the resource may be identified as surplus. Surpluses may be from (1) energy resulting from generation above firm commitment; (2) excess capacity usually available since long-term capacity will be exceeded nine out of ten years; (3) excess capacity resulting from the mechanical addition or modification to generating units by BOR; (4) and in general, capacity and energy amounts offered on a long-term basis that were not committed by contract. WAPA markets surpluses on a short-term basis as a component of its overall marketing program. The surplus resources are made available to existing customers first and then to the general market.

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 schedule. In anticipation of high inflow to Lake Powell, BOR may determine it is necessary to increase monthly release volumes, which translates 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.

REPAYMENT OF THE COLORADO RIVER STORAGE PROJECT

Section 5 of the original CRSP Act (P.L. 84-485) established the Upper Colorado River Basin Fund.

Revenues collected from the operation of the storage projects and participating projects are credited and made available for repaying the costs of operation, maintenance, and replacement of, and emergency expenditures for all CRSP projects. CRSP revenues come from three primary sources: (1) municipal and industrial water sales, (2) power sales, and (3) irrigation water sales. In addition, revenues from specific state projects may be allocated to repay specific project features and not be generally disbursed.

CONSULTATION PROCESS

The Secretary of the Interior is responsible for the operation, management, and maintenance of all Colorado River facilities authorized by Federal law. The Secretary has been directed to comply with the applicable provision of the Colorado River Compact, the Upper Colorado River Basin Act, the Boulder Canyon Project Act, the treaty with the United Mexican States, and the legal interpretations of Arizona v. California in the storage and release of water from the reservoirs in the Colorado River Basin.

If the Secretary of the Interior fails to comply with these laws, any state of the Colorado River Basin may maintain an action in the Supreme Court of the United States to enforce the legal mandates.

The Secretary of the Interior, through BOR, annually reviews the past year's operation of the Colorado River system and the proposed operation for the up-coming year. Determination of the specific annual goals are to comply with the existing legal mandates; follow, as closely as possible, the defined operating criteria; and be done in consultation with the seven Colorado River Basin states.

SUMMARY

The operational, structural, and climatic constraints that dictate the flow of the Colorado River are complex. A sophisticated system capable of responding to political and economic conditions is required. This system, including the constraints and legal criteria influencing the movement of water through Glen Canyon Dam, will 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 include:

(1) The Central Arizona Project, which will allow the state of Arizona to use its full Colorado River allocation and will reduce the amount of water currently available to the state of California.

(2) Native American Reservations in the Colorado River Basin, which have a Federally reserved right to a portion of Colorado River water. As development increases, Native American water rights will become more valuable.

(3) Ranchers and farmers, who are beginning to look at their water rights as their last harvestable crop, rights that can be marketed.

(4) The proposed sale of the state of Colorado water rights to San Diego, California, which has recently brought the issue of water rights sales and transfers into the legal arena.

(5) Public concerns over the impact of CRSP operations on legally protected natural resource values in the Colorado River Basin, which continue to increase over time.

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 form a management system that is not easily understood and is 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 to understand and explore ways that the system can be adjusted to better meet all the demands on the river.

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COLORADO RIVER WATER LAW: ITS DEVELOPMENT AND IMPACT ON THE OPERATIONS OF GLEN CANYON DAM

The management and operation of Glen Canyon Dam and the Colorado River Storage Project is defined by physical, legal, and system components. The determination of alternative flow opportunities for the operation of Glen Canyon Dam requires that the logic and boundaries for management be defined. The development of the water law for the Colorado River is briefly outlined from the initiation of irrigation in the early 1900s through the Colorado River Basin Salinity Control Act of 1974.

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INTRODUCTION

The Colorado River is the dominant river system in the southwestern United States. Over 20 million people depend upon it for drinking water, irrigation, electricity, and recreation. The river drains approximately one-twelfth of the continental United States as it flows from the Rocky Mountains to the Gulf of California. The Colorado River has figured prominently in the development of the area and is the lifeline of the Southwest.

The Colorado River has been regulated and manipulated since the 1800s, but the laws, treaties, compacts, agreements, and management mandates that define the operation of the river have often been in conflict. Today, the management and manipulation of the Colorado River is reflected by a myriad regulations, referred to as the "Law of the River."

It is the objective of this report to outline the history, laws, compacts, negotiations, and debates that have led to the present management and operation of the dams of the Colorado River Basin. The information presented addresses the basic laws which guide the Department of the Interior and the seven Colorado River Basin states in the management of the Colorado River system. It is not meant to be an in-depth analysis and interpretation of these laws or a delineation of all the facts, figures, and documents. Instead, it is to provide the Glen Canyon Environmental Studies research group with the background information necessary to understand the complexity of the operations of Glen Canyon Dam.

Several references have been used in the development of this report (Meyers 1967, Nathanson 1978, Olson 1926, U.S. Department of the Interior 1974, Weatherford and Brown 1986). The discussion presented here represents a consolidation of the information from these documents.

SYSTEM DESCRIPTION

The Colorado River Basin comprises 244,000 square miles and includes portions of seven western states (Wyoming, Colorado, Utah, New Mexico, Nevada, Arizona, and California) and Mexico. The basin is a geographic composite of high mountains and deserts. Thirteen major reservoirs and dams are managed to control the release and passage of water through the system. In addition, the state of Colorado has several trans-basin diversions which transport water to the eastern slope of the Rockies. The Central Utah Project will transport water from the Colorado River Basin to the Great Basin for use in the Salt Lake City area. The Central Arizona Project will allow for the diversion and transport of Colorado River water to the Phoenix and Tucson metropolitan areas.

The basin is drained by two major rivers: the Green River which originates in the Wind River Mountains in Wyoming and the Colorado River which begins in the Rocky Mountains in Colorado. These rivers join in southern Utah, flow southwesterly through Lake Powell, the Grand Canyon, and the deserts of Arizona, Nevada, and California, and eventually terminate in the Gulf of California. Along its 1,400 mile course, the Colorado River is fed by nine major tributaries. It ranks sixth in size among the nation's rivers.

Colorado River water is diverted for many uses and reuses. It has been stated that the Colorado River is one of the most over-appropriated and heavily utilized rivers of the world. Today, the reservoirs on the tributaries and mainstem store over 60 million acre-feet (maf) of water, produce over two million kilowatts of power, and annually export over five maf of water for use outside of the basin.

APPROPRIATIVE VERSUS RIPARIAN WATER RIGHTS

To gain perspective into the forces that have shaped the present legal framework for the Colorado River and the operation of Glen Canyon Dam, it is necessary to understand the concepts of the development of water law in the American West. United States water law in the early 1800s was based on the laws and customs that had been established by eastern and midwestern settlers who had sufficient water for their requirements. They did not need to put strict controls on how water was managed or used. The rights to use the water were based on the English Riparian Rights Doctrine which stated that any landowner had a right to use of water that flowed across his land as long as he returned it with its quantity and quality undiminished. The intent of the **Riparian Doctrine** was to keep the water in the stream to protect navigation and enhance the stream's ability to provide power.

The fact that water supplies of much of the western United States were limited, the water was needed away from the river channel, and the Federal Government owned the majority of Western land required that a modified means of water allocation be developed. During the late 1800s and early 1900s users who did not have direct access to or supply of water acquired it simply by diverting what they needed and putting the resource to a beneficial use. After numerous court arguments, it was determined that the "first in time, first in right" concept of appropriating water would be the guiding principle in the allocation of western water resources (Lavendar 1982).

An **appropriative** water right is based on having physical control and providing beneficial application of the water resource. An important aspect of this concept is that long-term storage is considered an acceptable exercise of an appropriative right. Rights to the use of the water are based on the date of initial appropriation and the application to a beneficial use.

In 1879, the U.S. Supreme Court recognized the rights to the Colorado River and reiterated that the appropriative doctrine was the primary legal tool for deciding rights (Lavendar 1982). The Federal Government of the United States still retains the sovereign power to control the water but the rights to use the water has been divided among the Colorado River Basin states based on negotiated compacts and agreements.

The management of the primary mainstem and tributary dams and reservoirs of the Colorado River system is the responsibility of the U.S. Department of the Interior in consultation with the seven Colorado River Basin states. The Secretary of the Interior is the defined Federal water master of the Colorado River. The Bureau of Reclamation (BOR) provides the primary management functions.

DEVELOPMENT OF THE COLORADO RIVER BASIN AND THE "LAW OF THE RIVER"

The development of the water resources of the Colorado River followed a much different path than that of the rest of the country. Since the Colorado River was the main source of water in the basin, many people were dependent upon it, but the cost of development and political requirements were greater then any one individual, group, or state could provide. To compensate for limited individual development ability, water user groups and other political associations were organized to work for water development of the Colorado River. The resulting coalitions, compromise, and agreements form the framework of today's Colorado River water law, the "Law of the River."

The development of the Colorado River Basin can be separated into several distinct periods of action and frameworks for management and operation.

1870-1900. The first documented use of Colorado River water was in 1877 when water was diverted by farmers in the Palo Verde area of Arizona. Several years later, farmers in the Yuma Valley and Imperial Valley started to divert water directly from the Colorado River to irrigate their crops. The acres of land requiring water increased as people settled the West and gained ownership of land through the Homestead Act of 1862, the Pacific Railway Act of 1864, and numerous land development schemes. In the late 1800s, approximately 80,000 acres of land were irrigated. By the 1980s, the number of acres had risen to over 500,000. This period of time also marked the completion of Major John Wesley Powell's historic voyages through the Grand Canyon and the initial discussions of how the waters of the Colorado River Basin should be managed.

1900-1910. During the early 1900s, major changes were initiated in the Colorado River Basin that had far-reaching effects on the future legal and institutional management of the Colorado River. The Federal

Government responded to pressures from several western states to initiate studies on determining the amount of irrigable lands in the Colorado River Basin. John Wesley Powell, Director of the U.S. Geological Survey, initiated studies that identified the amount of Colorado River Basin lands that could be irrigated, where reservoirs could be built to store the basin water, and where the water to fill the reservoirs was to come from. Powell did not believe that there was enough water in the Colorado River Basin to support the amount of land that the states wished to irrigate. The Colorado River Basin states feared the Federal Government was becoming too involved in the future management of western water.

Initially, the basin states held to their positions and limited the Federal Government's action. However, the economic depression of the 1890s, the lack of actual western development, and the large scale development prospects in the lower Colorado River Basin all combined to focus the need for a coordinated basin states approach. In 1902, with the backing of President Theodore Roosevelt, the **Reclamation Act of 1902** was passed, and the Federal Government became a major player in the development of the Colorado River Basin and the rest of the West. The Reclamation Act allowed for the creation of federally subsidized irrigation projects in the West and was the first step toward the development of federally sponsored water projects in the Colorado River Basin.

The U.S. Reclamation Service (Reclamation) was established in 1902 under the U.S. Geological Survey with the purpose of exploring the feasibility of irrigation projects and the development and management of the Colorado River. Two early initiatives set the tone and process that Reclamation would follow in subsequent years. The first initiative in the Colorado River Basin was the Yuma Project. This project, which eventually led to the building of the All-American Canal and Laguna Dam, was funded by bonds issued by a group of Yuma area people called the Yuma Water Users Association and were based on assessments levied to each of its members.

Equally important was the development of multi-purpose dams and control structures. The Roosevelt Dam on the Salt River in Arizona was initiated prior to the enactment of the Reclamation Act, but due to financial and hydrological problems it had not been completed by 1902. With the passage of the Reclamation Act, the area water users saw an opportunity to complete their project. Contracts for the dam's completion were made between the Salt River Valley Water Users Association and Reclamation. Roosevelt Dam represented the first storage reservoir for Reclamation and was also the first project to use hydropower revenues as a means of repaying the cost of the project. From this point on, hydropower was always considered in any Reclamation multi-purpose dam project.

Control of the highly variable annual flow of the Colorado River was necessary. J.P. Lippincott, the first chief of Reclamation, directed the writing of a report that outlined the potential lower river dam sites. Lippincott, with the assistance of the Assistant Chief Engineer, Arthur Powell Davis (nephew of Major John Wesley Powell), identified the opportunities for diversion of irrigation water along the Arizona-California section of the river. Their recommendations were to initiate a study of two projects: (1) a storage dam in the Boulder Canyon area and (2) Laguna Dam, a structure to divert water from the Colorado River to irrigable land in California and Arizona.

The importance of Native American rights to the waters of the Colorado River Basin was determined by the Supreme Court in 1908 with the settlement of the United States v. Winters lawsuit. In this decision, the Supreme Court ruled that when the United States established the reservations, they had also reserved enough water to convert the Native Americans to an agricultural way of life. These rights to the water were "reserved" until the Native Americans could make use of them. The priority date for such "reserved rights" was determined to be that of the establishment of individual reservations. The 1908 Winters Doctrine court decision continues to play an important role in Colorado River politics.

1910-1925. The early irrigation development of the Colorado River took place in California and Arizona. In 1900, the California Development Company claimed 20,000 acre-feet (af) of Colorado River water and began diverting it, through Mexico, to the Imperial Valley (Salton Sink) area of California. After a series of corporate struggles, the water distribution system was purchased by the Southern Pacific Railroad.

In August 1905, the Colorado River breached the distribution canal and flowed uncontrollably into the Imperial Valley of California, eventually creating the landlocked Salton Sea. It took until February 1907 to close the breach in the canal. The farmers understood the need for a dependable water supply for crops, but also realized that the high cost to secure the supply could not be borne by any individual. In 1911, the farmers formed the Imperial Irrigation District and purchased the Southern Pacific Railroad's Colorado River water right.

Reacting to a need for a coordinated approach to Colorado River Basin development, an organizational meeting of the seven Colorado River Basin states (and originally Texas and Oklahoma) was held in 1917. Representatives of the Colorado River Basin states met to discuss the use of water supplies of the Colorado River and its tributaries. The state representatives formed an organization called the **"League of the Southwest,"** with the primary purpose to work for the development of the resources of the Colorado River.

The League worked diligently on water issues from 1920 to 1924 and were instrumental in initiating negotiations for the Colorado River Compact. At the urging of the Imperial Irrigation District and state of California, A.P. Davis, Acting Chief of Reclamation, revived studies of the irrigation canal for the Imperial Valley (the All-American Canal), and Congress authorized money to collect field data to evaluate canal options and potential Colorado River storage sites.

Their efforts led to the completion of the **Fall-Davis Report** (named for Secretary of the Interior Albert Fall and Arthur Powell Davis), which recommended that the All-American Canal be built from the Colorado River to the Imperial Valley and that a "high storage dam be built at or near Boulder Canyon" (S. Doc. 142, 67th Congress). The report suggested that the dam be a multi-purpose facility, combining storage, flood control, irrigation, and power generation. In April 1922, a congressman and a senator from California, Phil Swing and Hiram Johnson, introduced a bill to implement the report's recommendations. The bill did not have enough support and was defeated (Cong. Rec., 67th Congress, 2nd Session 1922).

The early 1920s was a volatile time in the history of Colorado River politics. While the Lower Basin states (California, Arizona, and Nevada) were trying to gain approval for the All-American Canal and the Boulder Canyon Dam, the Upper Basin states (Colorado, Utah, Wyoming, and New Mexico) were concerned that the Lower Basin states were gaining an advantage in the appropriation and rights to the Colorado River water. Of further concern was a Supreme Court ruling in a

Wyoming water rights case that determined that the rule of priority of use applied regardless of state lines.

Congress was not amenable to appropriate any money for Colorado River Basin development until agreements on future land use and basin water allocation had been reached. In 1921, a Colorado River Commission was authorized by separate acts of Congress and the legislatures of the seven Colorado River Basin states with the express purpose to negotiate the apportionment of the Colorado River. In 1922, the Commission was charged by Congress with the development of a Colorado River Basin compact, and Herbert Hoover, Secretary of Commerce, was appointed chairman.

The Commissioners met over a nine-month period, but could not agree upon apportionments among the seven states. An agreement could not be reached on individual state apportionments; however, a compromise was negotiated for the division of water between the upper and lower sections of the basin. After 27 meetings, an agreement was reached and the **Colorado River Compact** was signed on November 24, 1922, at the Bishop Lodge in Santa Fe, New Mexico. By the end of 1923, the Compact had been ratified by six of the seven basin states. Arizona was not to ratify the Compact until February 1944 after a series of court cases.

The Compact divided the water between the Upper and Lower Colorado River Basins and defined Lees Ferry as the official accounting location, or Compact Point. Each basin was apportioned the right to 7.5 maf of water per year from the Colorado River system based on an assumed annual basin yield of 15 maf. (Later years proved the 15 maf yield estimate to be higher than the average.) In addition, the Lower Basin was given the right to increase its use by one million acre-feet in any given year. Water for the country of Mexico was to come out of annual surpluses and if insufficient, the burden of deficiency would be equally borne by both basins. The Upper Basin could not cause the flow at Lees Ferry to be depleted below 75 maf for any period of ten consecutive years.

Concurrent with the negotiations for the Colorado River Compact, studies were completed that outlined the potential development of the lower Colorado River. Extensive congressional review of the proposals was initiated and led to the reintroduction (in 1925) of the Swing-Johnson legislation for the Boulder Canyon Dam.

1925-1940. The **Boulder Canyon Act** (45 Stat. 1064, 43 U.S.C.) was finally passed on December 21, 1928, and the prospect of a control dam on the Colorado River became a reality. The primary purposes of the Boulder Canyon Project included: flood control, improvement of navigation, regulation of flows, storage and delivery of water for reclamation and other beneficial uses, and generation of power. The Act officially approved the Colorado River Compact, authorized the building of the All-American Canal, and Boulder Dam and Powerplant, and authorized the investigation of possible reclamation projects in every basin state but California.

A requirement of the Act was that before it could become effective, the state of California had to adopt legislation that would set a limit on its use of Colorado River water. This constraint to project enactment was lifted with the passage of the **California Limitations Act** in June 1929. This Act limited California to 4.4 maf of water per year plus one-half of all surplus water.

Upon enactment of the California Limitations Act, contracts were immediately initiated with California municipalities and agencies for the power and water available from the Boulder Canyon project. These contracts would provide revenue for repayment of the dam and powerplant and provide for operation and maintenance costs. In 1930, California agreed to purchase all the electricity and thereby underwrite the cost of the dam and powerplant. Boulder Dam (later renamed Hoover Dam) construction began in 1931 and was completed in 1935. Lake Mead water storage began on February 1, 1935, and power generation began on September 11, 1936. The 50-year power contracts were initiated on June 1, 1937.

1940-1970. The country of Mexico felt that it was being left out of the official division of Colorado River water and that a formal recognition of its right was necessary. In 1939, the Rio Colorado Irrigation District, a group of northern Mexican farmers, was organized in the Mexicali Valley to assist Mexico's claim for Colorado River Water. In 1941, the Mexican ambassador presented the United States with a draft treaty for the division of the waters. The U.S., eager to satisfy Mexico and retain it as an ally during World War II, ratified and proclaimed official the **Mexican Water Treaty** in 1944.

The treaty guaranteed the country of Mexico a minimum of 1.5 maf of Colorado River water annually. Davis Dam was authorized to be built to reregulate the flows in the river and the **International Boundary Water Commission** was established to administer the water transfer. In the event of an extraordinary drought, Mexican deliveries will be reduced in the same proportion as the consumptive uses in the United States.

The Upper Basin states were concerned that the Lower Basin was developing at a much quicker pace and that the application of Colorado River water to Lower Basin beneficial uses and the Mexican Treaty could force them to relinquish some of their water. Their concern prompted them to organize an Upper Colorado River Commission to study the allocation of water among the Upper Basin states and to develop a plan for the development of the water resources of the Upper Colorado River Basin.

The need for Upper Basin storage was envisioned when the Colorado River Compact was negotiated in 1922. The allocation of Colorado River Water between the Upper and Lower Basins was contingent upon the Upper Basin delivering the water. In order to achieve the delivery requirements, Upper Basin storage was necessary. Developing the storage required an agreement on water allocation among the Upper Basin states.

An **Upper Colorado River Compact** was negotiated in 1948 among the five Upper Colorado River Basin states. The compact stipulates that Colorado would receive 51.75 percent, New Mexico 11.25 percent, Utah 23 percent, and Wyoming 14 percent. In addition, Arizona is granted 50,000 af annually. An interstate agency was organized to facilitate the coordination between the states with the Upper Colorado River Commission serving as the entity to facilitate Upper Colorado River Basin water decisions.

The Upper Colorado River Commission immediately initiated the study of potential water developments in the Upper Basin. Project reports were prepared in 1951 and 1952. These reports were the basis for the development of the **Colorado River Storage Project (CRSP) Act** (43 P.L. 84-485, 70 Stat. 105). The CRSP Act passed on April 11, 1956, authorized four major storage units in the Upper Colorado River Basin and eleven participating water projects. The participating projects used revenues generated from the hydroelectric plants to help repay the costs of irrigation features that were beyond the ability of the water users to pay. The CRSP purposes were defined as: (1) to regulate the flow the Colorado River, (2) to store water for beneficial consumptive use, (3) to provide for the reclamation of arid and semiarid land and flood control, and (4) to generate hydroelectric power as incidental to the other project purposes.

From 1957 to 1963, construction of the storage projects was initiated and completed. Construction of Glen Canyon Dam, the key regulatory feature and primary revenue producer, began on October 1956 and was completed in September 1963. The Filling Criteria were established for Glen Canyon Dam by the Secretary of the Interior, Stewart Udall, on July 19, 1962. Glen Canyon Dam officially began to store water in Lake Powell on March 13, 1963, and the filling criteria remained in effect until June 1980 when they expired as Lake Powell reached its full storage capacity of 27 maf.

During this same period, the state of Arizona was attempting to gain authorization for the Central Arizona Project (CAP). Arizona had been trying since it ratified the Colorado River Compact in 1944 to develop the waters of the Colorado River for its use. The Bureau of Reclamation (BOR) prepared a report in 1947 that determined that the transport of Colorado River water to central Arizona was feasible from both an engineering and financial point of view. Congressional consideration of the Central Arizona Project began in the 78th Congress but made little progress until the 90th Congress. At that time, it was determined that no further study would be done until the waters of the Lower Colorado River Basin were either adjudicated and made binding or a mutual agreement as to their use could be made.

In order to further their cause for the Central Arizona Project, Arizona initiated a suit against California in 1952 requesting that Arizona's right to Colorado River water be accepted at 3.8 maf of water. A special water master of the courts was appointed to determine what the Arizona appropriation should be.

In 1964, after eleven years of review, the U.S. Supreme Court decreed that if sufficient mainstem water were available to satisfy the 7.5 maf per year consumptive use in the Lower Basin, then Arizona would be apportioned 2.8 maf per year plus all of the water in its tributaries. California was apportioned 4.4 maf per year; Nevada, 0.3 maf per year. If surplus water exceeded the allocated 7.5 maf level, then California and Arizona would be apportioned 50 percent of the surplus, and the United States would have the right to contract with Nevada for 4 percent of Arizona's share.

In addition, five of the 25 Native American reservations in the Lower Basin were allocated future water rights under the Winters Doctrine. The five reservations were the Chemehuevi, Cocopah, Fort Yuma, Colorado River, and Fort Mohave.

In 1968, during the 90th Congress, Public Law No. 90-537, the **Colorado River Basin Project Act**, was signed into law. The law authorized the CAP; gave California and existing Arizona and Nevada water users priority over CAP water users; assumed the Mexican Water Treaty as a national obligation; established priorities for the coordinated long-range operation of the major Colorado River reservoirs (operating criteria); gave states the right to sue the United States if the Federal Government fails to comply with the "Law of the River;" and established Federal electrical capacity at the Navajo Powerplant, a feature of the CAP. The Navajo Powerplant was added both to generate electricity for the purposes of the CAP and as a trade-off for dams that had been recommended in the Grand Canyon.

The Operating Criteria for the major Colorado River reservoirs included meeting the following priorities: the treaty with Mexico, an Upper Basin guarantee of providing 7.5 maf of water per year to the Lower Basin, carry-over storage given preference to meet the 7.5 maf target, and parity in storage between Lake Mead and Lake Powell.

The Section 602(a) of Public Law 90-537 is important to the operation of Glen Canyon Dam. Specifically, if the Upper Basin forecasted storage is less than the 7.5 maf requirement, or if Lake Powell active storage (water than can be delivered downstream) is less than Lake Mead active storage, then a minimum release schedule of 8.23 maf will be followed. However, if the forecasted storage is greater than the 602(a) requirements, operations at Glen Canyon Dam should be regulated to release water from Lake Powell to Lake Mead as long as Lake Powell has greater storage than Lake Mead, or, if Lake Powell storage is equal to Lake Mead, or to avoid spills from Lake Powell. Within the annual and monthly releases set by BOR, daily releases are scheduled by Western Area Power Administration (WAPA) to meet contractual obligations to power customers.

The Operating Criteria were issued in June 1970 by the Secretary of the Interior. They have as their objective the release of a minimum of 8.23 maf per year at Lees Ferry and require that a reservoir operating plan be developed by the Secretary each year after consultation with the seven basin states and that a review of the criteria is made every five years.

The last Federal legislation impacting the management of the Colorado River occurred on August 30, 1973, with the agreement between the country of Mexico and the United States on the quality of water to be delivered to Mexico. Minute 242 of the International Boundary and Water Commission set annual salinity levels based on water being diverted to Imperial Valley. The agreement with Mexico precipitated the passage of the **Colorado River Basin Salinity Control Act** in June 1974 (P.L. 93-32, 88 Stat. 266).

The congressional acts, compacts, contracts, court decrees, treaty, and administrative regulations which comprise the "Law of the River" establish the maximum amount of water available for use within each state in the Colorado River Basin.

The actual quantity of Colorado River water available for allocation each year may be more or less than the established ceilings, since the shares are an apportionment of a total supply. These shares are dependent upon annual runoff quantities, available storage space in the reservoirs, and extent of use and depletion by the basin states.

ANNUAL MANAGEMENT OF THE COLORADO RIVER

The overall management of the Colorado River is the joint responsibility of the Federal Government, through the Secretary of the Interior, and the seven Colorado River Basin states. The Secretary of the Interior is the designated water master of the Colorado River. BOR has been given the responsibility to perform the actual management of the river system in consultation with the Colorado River Basin states. Since 1977, WAPA, U.S. Department of Energy, has been responsible for marketing of the electrical energy and capacity developed at the dams. The management of the natural and recreational resources of the Colorado River is the responsibility of a variety of Federal and state offices. Included are the National Park Service, the Fish and Wildlife Service, the Bureau of Land Management, the Bureau of Indian Affairs, the U.S. Forest Service, and the seven Colorado River Basin states.

BOR prepares an Annual Operations Plan (AOP) for the Colorado River and consults on it with the states. The

AOP takes into account available reservoir storage, operation targets, maintenance requirements, and special operation needs.

The operating criteria for reservoirs of the Colorado River system were set in Public Law 90-537, the Colorado River Basin Project Act. The criteria are reviewed formally every five years by the Secretary of the Interior in consultation with the seven Colorado River Basin states. Management of the operation of Glen Canyon Dam on a monthly, daily, and hourly basis is based on meeting the defined annual criteria, avoidance of spilling or bypassing water, and on providing, as an incidental objective, for the generation of hydropower.

The annual goal in the management of Lake Powell is to have a full reservoir (27 maf) by July of each year. Based on historical knowledge of average runoff, a target volume of 22.6 maf, or 4.5 maf of available storage, is strived for on January 1st of each year. With the availability of over 4 maf of storage and the capability to pass 1.1 maf of water through the eight generators each month, the objective of a full Lake Powell by July can be met without having to spill or bypass water. Studies are currently on-going to determine the risk of spilling or bypassing water.

Monthly volumes of water passed through the Glen Canyon Dam powerplant are a function of meeting the annual obligations, achieving reservoir storage targets and providing for the generation of hydro-electricity. BOR determines the annual and monthly release volumes, The monthly volumes are then managed daily, hourly, and by the minute by WAPA, within the constraints of the defined operating criteria.

Any changes in the criteria of operation for Glen Canyon Dam must go through a consultation process with the Colorado River Basin states. If, after development of the operation changes and impacts, it is determined that a modification of the operational criteria is required, a formal review process will be initiated.

FUTURE CONSTRAINTS TO USES OF THE COLORADO RIVER

While the "Law of the River" identifies the apportionment of Colorado River water, there are many areas where the future of the Basin water is uncertain. Significant areas of future conflict include the determination of the actual amount of Mexican water delivery owed by the Upper Basin states, Operating Criteria of Upper Basin reservoirs, Native American water rights, inter-basin transfer of water, and depletion allowances.

Mexican Water Delivery. The Mexican Water Treaty of 1944 requires a delivery of 1.5 maf of water annually of Colorado River from the United States. The treaty requires that the Upper Basin states satisfy one-half of the delivery obligation that cannot be met from surplus water. The Lower Basin believes that there is no surplus and that the Upper Basin should supply an additional 750,000 af per year plus delivery losses. The Upper Basin contends that there is no shortage and that sufficient water exists to meet all obligations.

Present Upper Basin water-supplies allow for the annual minimum release of 7.5 maf plus the 750,000 af Mexican Treaty requirement, minus 200,000 af provided by the flows from the Paria River. This constitutes the 8.23 maf operation release. The issue of the Mexican Water Delivery requirements will require additional negotiation, but the present water depletion levels in the Upper Basin, do not pose an immediate need to refine the allocation requirement.

Native American Water Rights. Water rights for five Native American reservations along the Colorado River below Lake Mead were defined in 1963 by the U.S. Supreme Court. In the suit Arizona v. California (March 9, 1964, 376 U.S. 340), the Court determined that "enough water was reserved to irrigate all the practicably irrigable acreage of the Reservations." The Native American reservations involved in the definition of allowable irrigable acreage are the Cocopah, Chemehuevi, Colorado River, Fort Mohave, and Fort Yuma. These reservations represent five of the 25 reservations in the lower Colorado River basin.

At question is the amount of water that the tribes hold as a function of their prior rights to water within the Colorado River Basin, defined as the "Present Perfected Right." All Tribal water rights are to be met out of Arizona's and California's apportionment. The conflict arises in years when the flow of the Colorado River is below 7.5 maf. During these years, the Present Perfected Rights are to be satisfied first, giving the Native American tribes priority over Arizona's CAP and limiting California to 4.4 maf.

Operating Criteria for the Upper Basin Reservoirs. With the filling of the major reservoirs of the Upper

Colorado River Basin during the early 1980s, the ability to store excess water within the Basin has been reduced and the probability of having to bypass water around the powerplant at Glen Canyon Dam has been increased. Specific target elevations and volumes have been defined for each reservoir on the Upper Colorado River Basin. Operational management targets and levels must now be established and included in the management philosophy of Glen Canyon Dam to avoid bypassing of water during the runoff period.

Inter-basin and Trans-basin Water Transfers. Inter-basin and trans-basin diversions of water within the Colorado River system have been a part of the development of the Colorado River Basin from the very beginning. The Big-Thompson Project in Colorado initiated the diversion of Colorado River water to the Eastern slope of Colorado as early as 1937. Metropolitan Water District began withdrawing Colorado River water in 1941 and transporting it to the Los Angeles Basin.

In 1982, a proposal was made for the transfer of water from the Yampa River Basin (a tributary of the Green River) to the City of San Diego, California. The initial proposal was for San Diego to lease the water for a specified number of years. The involved basin states have rejected the proposal, but as water pressures increase in the Lower Basin, similar alternative water movement scenarios will again be proposed.

Depletions in the Upper Basin. The proposed development of the water resources of the Upper Colorado River Basin has been slowed due to the drop in the requirements of the energy industry, over-estimation of water needs, and a slower economy. The full development of the water of the Upper Colorado Basin is predicted to occur somewhere around the year 2040.

Each state has developed long-term goals for water development. However, the actual amount of water that is available for development and depletion is less than the original 7.5 maf defined by the Colorado River Compact. Due to the overestimation of available water supply, the actual amount of water that would be available during a dry year is in the range of 5.8 to 6.3 maf. As yet, this is not a problem for any state, except New Mexico which has already reached its depletion limit defined by the Compact.

Consultation with the Seven Basin States. The Secretary of the Interior is responsible for the overall management of the Federal dams on the Colorado River.

The responsibility is defined and articulated throughout the legal mandates and court decisions which compose the "Law of the River." A key area of importance is that the Secretary of the Interior must consult with the seven Colorado River Basin states prior to enacting any operational changes at the dams. This is to ensure that the basin states have an opportunity to review the proposed changes and potential impacts prior to enactment. If the Secretary fails to comply with this, the states can enjoin the Secretary from making the change.

Any operation change at Glen Canyon Dam will require a consultation period with the Colorado River Basin states prior to initiation of any National Environmental Policy Act review.

Priorities of Operation. The balancing of the releases of water from Glen Canyon Dam to meet downstream water allocations, power generation, environmental requirements, and recreation needs will continue to be an area of discussion. Early development of the Colorado River was based primarily on the societal and development needs of the seven basin states. Power generation was added to the appropriate facilities as a means to repay the cost of construction, support other projects, and to provide for operation and maintenance needs. The environmental and recreation aspects were not fully articulated into the management of the operation of the river system.

The Secretary of the Interior, as overall manager of the Colorado River dam system, must make the determination of which aspects of operation take priority in management. Conservation of water is of primary importance. The balancing of the remainder of the issues will require the development of an adaptive and flexible approach to management, an approach which will require consultation with the seven Colorado River Basin states and the other resource management entities in the Colorado River Basin.

Water Quality. The water quality of the Colorado River was originally focused on the levels of salinity associated with the Mexican water deliveries. Water quality standards have not been set by each of the seven basin states. Instead, in 1973, the states addressed the basin salinity problem by establishing the Colorado River Basin Salinity Control Forum. The Forum represents the states of the Colorado River Basin and has set salinity standards for specific locations in the Colorado River. The Colorado River Salinity

Control Act of 1974 and the revisions of 1978 focus the efforts of salinity control at construction of salinity control projects and a desalinization plant.

Additional water quality problems have been identified in the Colorado River Basin. The effects of agricultural return flows and natural sources of selenium, boron, and other minerals and metals will need to be addressed in the future.

The handling of these and other future water quality impacts go beyond the jurisdiction of the Salinity Control Act. Future control will also be focused through interpretations of the Clean Water Act, the Endangered Species Act, the Fish and Wildlife Coordination Act, and other appurtenant state and Federal legislation.

SUMMARY

The Colorado River is the thread that ties the Colorado River Basin together. Its development has been molded around the negotiation and development of laws, compacts, treaties, and agreements that define the amount of water that flows down the river channel.

While a great deal of tradition has defined the operation of the River, we are entering a volatile time in its management. The era of development of the major storage and irrigation projects has ended. The future management of the river will depend upon integrating the "Law of the River" with the quantity of basin water, the other demands on the Colorado River, and coordination between the states and the Federal Government.

How will Colorado River operation decisions be made in the future? How will managers of the often conflicting goals resolve the differences? These questions and many more like them are being formulated and asked today. The Colorado River is the lifeblood of the American Southwest. Directly and indirectly it impacts all the people of the Southwest. Its development as a usable and consistent resource has been accomplished by people who believed in the expansion of the resources and economic worth of the Colorado River Basin. Today, the management of the Colorado River has increased in difficulty as additional environmental and recreational factors have been added to the equation.

The resources of the Colorado River are limited. Limited by the actual amount of water available and limited by the legal and management concerns. Change in the Colorado River Basin is inevitable. The challenge for the decision-makers and managers is to develop a flexible and adaptive program that allows the Department of the Interior and the Colorado River Basin states to meet their legally mandated obligations and allow the interaction of the other aspects of operations, the environment, recreation, and other natural resource components into the process.

The challenge is to develop an adaptive management plan that allows for evaluation of trade-offs and determination of opportunities to maximize the integration of operations and the other resources of the Colorado River.

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