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Abstract The Colorado River is one of the most highly regulated and extensively utilized rivers in the world. Total reservoir storage is approximately four times the mean annual runoff of ~17×10^9 m^3 $year^{-1}$. Reservoir storage and regulation have decreased annual peak discharges and hydroelectric power generation has increased daily flow variability. In recent years, the incidental impacts of this development have become apparent especially along the Colorado River through Grand Canyon National Park downstream from Glen Canyon Dam and caused widespread concern. Since the completion of Glen Canyon Dam, the number and size of sand bars, which are used by recreational river runners and form the habitat for native fishes, have decreased substantially. Following an extensive hydrological and geomorphic investigation, an experimental flood release from the Glen Canyon Dam was proposed to determine whether sand bars would be rebuilt by a relatively brief period of flow substantially greater than the normal operating regime. This proposed release, however, was constrained by the Law of the River, the body of law developed over 70 years to control and distribute Colorado River water, the needs of hydropower users and those dependent upon hydropower revenues, and the physical constraints of the dam itself. A compromise was reached following often difficult negotiations and an experimental flood to rebuild sand bars was released in 1996. This flood, and the process by which it came about, gives hope to resolving the difficult and pervasive problem of allocation of water resources among competing interests.

Histoire de la crue artificielle du Colorado dans le Grand Canyon

Résumé Parmi les fleuves du monde, le Colorado est l'un des plus réglementés et des plus utilisés. La capacité totale de stockage des réservoirs représente approximativement quatre fois l'écoulement annuel moyen (~17×10^9 m^3 an^{-1}). Le stockage en réservoirs et la réglementation ont amené une diminution des débits annuels maximaux alors que la production hydroélectrique a accru les variations journalières de l'écoulement. Au cours de ces dernières années, les effets secondaires de ce mode de gestion sont devenus de plus en plus évidents, en particulier dans le parc national du Grand Canyon en aval du barrage de Glen Canyon, et sont à l'origine de nombreuses inquiétudes. Depuis l'achèvement du barrage de Glen Canyon, le nombre et la taille des barres de sable, qui sont utilisés par les amateurs de descente de rivière et qui constituent l'habitat des poissons autochtones, ont considérablement diminué. A la suite d'une étude hydrologique et géomorphologique approfondie, une crue artificielle à partir du barrage de Glen Canyon a été proposée pour déterminer si une période relativement brève d'écoulement à débit beaucoup plus élevé que la normale permettrait la reconstitution des barres. La faisabilité de cette crue artificielle était cependant limitée par la Loi du Fleuve (l'ensemble des lois adoptées au cours des 70 dernières années pour contrôler et distribuer l'eau du Colorado), par les besoins des utilisateurs d'énergie hydroélectrique et de ceux qui dépendent des revenus de cette énergie, et par les contraintes physiques du barrage lui-même. Un compromis a cependant été établi à la suite de négociations souvent difficiles et une crue artificielle expérimentale a pu être réalisée en 1996. Cette crue, et la procédure qui l'a rendu possible, ouvrent la porte à une solution au problème difficile et une crue artificielle expérimentale a pu être réalisée en 1996.

Open for discussion until 1 February 2001

INTRODUCTION

The Colorado River is one of the most highly regulated rivers in the world. Total reservoir storage capacity exceeds four times the mean annual flow of approximately 17×10^9 m^3 $year^{-1}$. The largest reservoir, Lake Powell, formed by Glen Canyon Dam, has a usable capacity of approximately 30×10^9 m^3. The relatively large reservoir storage capacity permits the highly variable basin runoff to be extensively utilized for agriculture, industrial, and municipal needs. Except during periods of unusually large runoff, the entire flow of the Colorado River is diverted and consumed before reaching the sea.

The primary purpose of Glen Canyon Dam, which was completed in 1963, is to allocate runoff between the Upper Basin states: Utah, Wyoming, Colorado, and New Mexico, and the Lower Basin states: Arizona, California, and Nevada, as provided by the 1922 Colorado River Compact. Hydroelectric power generation is an incidental, though significant, purpose of the dam.

The construction and operation of Glen Canyon Dam altered the Colorado River downstream through Grand Canyon National Park by stabilizing the flow, and reducing water temperature and sediment loads. Not surprisingly, these alterations and the many values of the Colorado River have produced continuous and long-lasting conflicts. These conflicts are frequently exacerbated by a lack of information concerning the nature of the undeveloped Colorado River, as few scientific studies were conducted prior to the completion of Glen Canyon Dam.

In the early 1970s, the US Bureau of Reclamation proposed to rebuild the turbines in Glen Canyon Dam. Rebuilt turbines would permit any increase in the already large daily fluctuations of water levels through Grand Canyon. This possibility caused citizens, environmental organizations and whitewater tour operators to become concerned. After several legal challenges to the operations of the dam, the Bureau of Reclamation initiated the Glen Canyon Environmental Studies (GCES) to assess the impacts of the dam and its operations through Grand Canyon, from the dam to Lake Mead. The Glen Canyon Environmental Studies were directed to investigate and evaluate the effects of storage and power plant operations on basic hydrological and biological processes as well as examining economic, political and legal issues related to managing the dam (Water Science and Technology Board, 1987).

One result of the GCES was an experimental flood in the spring of 1996. The flood was proposed as a way to determine whether it was possible to rebuild sand bars along the channel margin. The hypothesis leading to the flood flow was not part of the original GCES plan. Rather, it developed during GCES studies and had to overcome various legal, economic and physical impediments before it was completed.

ALTERATION OF THE COLORADO RIVER BELOW GLEN CANYON DAM RIVER DISCHARGE

Glen Canyon Dam is located 23 km upstream from Lees Ferry, Arizona and the boundary of Grand Canyon National Park (Fig. 1). A gauging station has been operated at Lees Ferry since 8 May 1921 to determine flow from the Upper Basin of the Colorado River to the Lower Basin. The local boundary dividing the Upper Basin

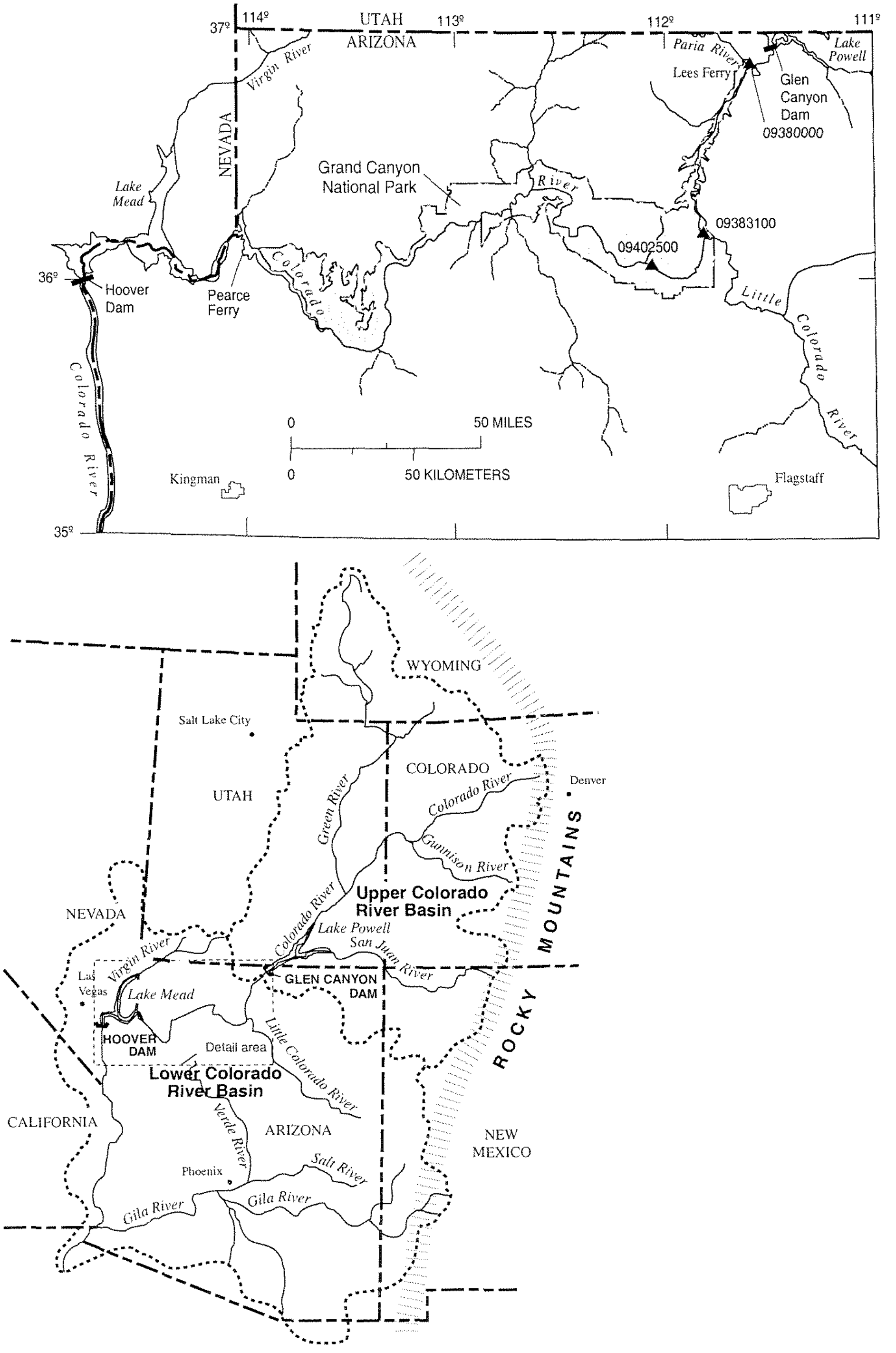

Fig. 1 Map of the Colorado River downstream from Glen Canyon Dam showing the location of selected gauging stations.

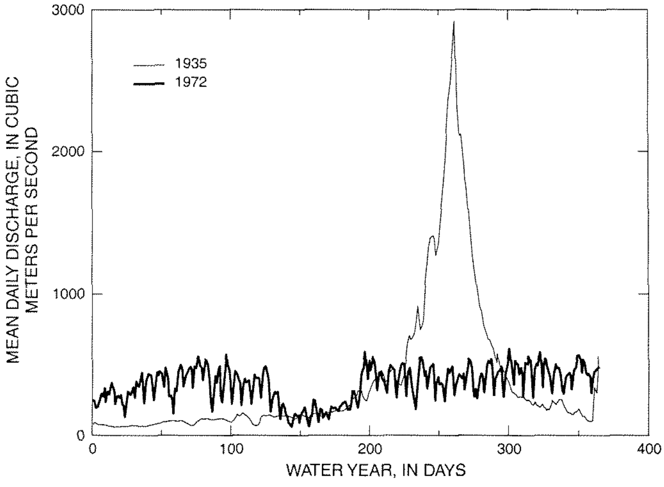

Fig. 2 Comparison of annual hydrographs at the Colorado River at Lees Ferry, Arizona, before (1935) and after (1972) the completion of Glen Canyon Dam in 1963.

from the Lower, known as the "compact point," is 400 m downstream from the mouth of the Paria River. Except for occasional contributions of flow from small tributaries, the Colorado River at Lees Ferry is completely regulated by Glen Canyon Dam. Annual hydrographs of the Colorado River recorded at the Lees Ferry gauge are compared for two years in Fig. 2: 1935 pre-reservoir/unregulated and 1972 post reservoir/regulated. The selected annual hydrographs are typical of the pre- and post-reservoir conditions. The total volume of runoff in both years was nearly identical, 15.2×10^9 m^3 and slightly less than the long-term average natural flow of 16.8×10^9 m^3.

Prior to the completion of Glen Canyon Dam, peak river discharges occurred in May and June, fed by snowmelt in the Rocky Mountains. The peak discharge during the 1935 flood was 2970 m^3 s^{-1}. After the spring snowmelt flood subsided, flow in the Colorado River typically receded to less than 200 m^3 s^{-1}, except during brief, but substantial tributary flash floods. One such flood occurred on 30 September 1935, at the end of the water year. The largest of these tributary floods increased the flow of the Colorado River to the magnitude of the annual snowmelt peaks, as well as contributing millions of tons of sediment.

Annual peak discharges of the Colorado River recorded at the Lees Ferry gauging station since it was established in 1921 are shown in Fig. 3. Prior to the construction of Glen Canyon Dam, 1921–1957, the natural mean annual peak discharge was 2420 m^3 s^{-1}, approximately twice the magnitude of the experimental flood. The peak recorded discharge was approximately 6230 m^3 s^{-1}. High water marks in the vicinity of Lees Ferry indicate that a flood of about 11 000 m^3 s^{-1} occurred during the late 1800s. Four of the unregulated natural annual peak discharge water years: 1931, 1934, 1954, and 1955, were less than 1275 m^3 s^{-1}, the 1996 experimental flood discharge. The smallest annual peak discharge was just 720 m^3 s^{-1} in 1934.

Colorado River flows recorded at Lees Ferry were affected to varying degrees during the construction of Glen Canyon Dam, however, substantial regulation began on 7 July 1965, when the first bypass tunnel was sealed. Since 1965, the regulated

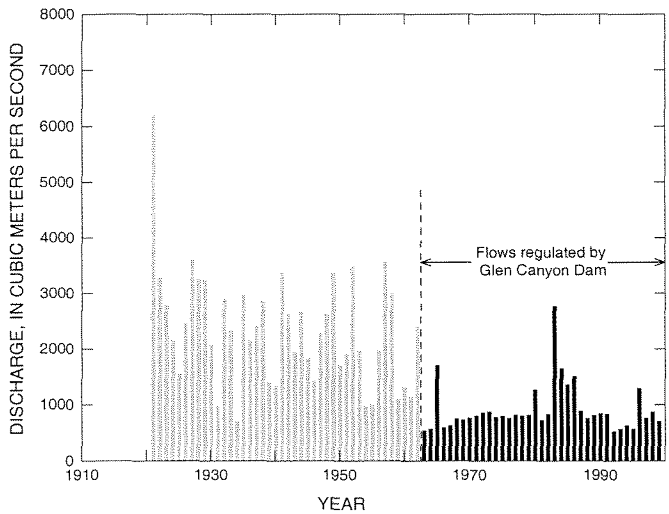

Fig. 3 Annual peak discharges of the Colorado River at Lees Ferry since 1921.

mean annual peak discharge of the Colorado River at Lees Ferry is 920 $m^3 s^{-1}$. In most years, 26 of 32, the annual peak discharge was less than the hydroelectric power plant capacity of approximately 930 $m^3 s^{-1}$.

Flow regulation by Glen Canyon Dam has substantially reduced the annual range of river discharge at Lees Ferry. Peak discharges are greatly reduced while low to intermediate flows are significantly increased (see Fig. 2). During 1972, the peak discharge was 867 $m^3 s^{-1}$. The spring snowmelt flood was completely eliminated. Then, water stored during the spring runoff is released throughout the remainder of the year. Except for the period of the snowmelt flood, May–July, the mean daily discharge has increased throughout the post-reservoir period. The volume of water released in a given month varies only by a factor of two throughout the year and reflects demand for electrical power in the southwest, rather than basin runoff. Typically, the largest monthly releases occur during December and January when electricity is needed for heating and during July and August when electricity is needed for air conditioning and water pumping. Flow regulation and the desire to maximize the generation of hydroelectric power by Glen Canyon Dam have greatly reduced flow variability through a year, but increased the typical daily range of flow.

The prominent flow fluctuations in the 1972 hydrograph (Fig. 2) are a result of the weekly variations in electrical power demand. Glen Canyon Dam is operated to generate electrical power during periods of peak demand; when electrical power usage falls, flow through the power plant is curtailed. Significantly less electrical power is needed on weekends, and flow releases from Glen Canyon Dam decrease accordingly.

The demand for electrical power also varies significantly during a day. Peak demand occurs during the morning and evening, while minimum demand occurs after 10:00 p.m. Hydropower facilities, such as Glen Canyon Dam, can respond to variation in demand more efficiently than thermal generation facilities. Consequently, flow releases from Glen Canyon Dam fluctuate substantially during a typical weekday. Instantaneous discharge of the Colorado River at Lees Ferry from 23 July to 7 August

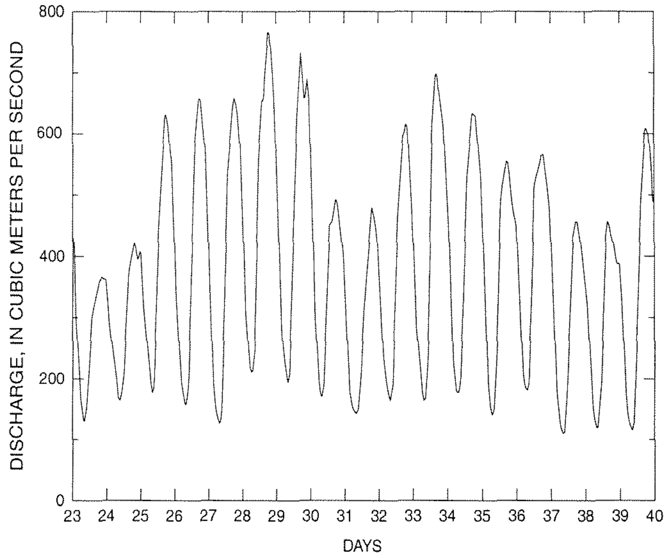

Fig. 4 Hydrograph of the Colorado River at Lees Ferry, Arizona, from 23 July to 7 August 1988. Variation in streamflow reflects the daily demand for electrical power in southwest US.

1988, is shown in Fig. 4. River discharge varied from a low of 109 $m^3 s^{-1}$ to a peak of 770 $m^3 s^{-1}$. The daily change in water surface elevation exceeded 4 m in some downstream reaches. Operation of the Glen Canyon Dam power plant to meet electrical power demand has greatly increased the daily range of discharge and river stage compared to the natural, unregulated flows. Prior to the construction of Glen Canyon Dam, only relatively large and infrequent tributary flash floods produced similar daily changes in flow. The daily range and maximum hourly change of power plant flow releases have been limited since 1992 to reduce ecological and physical impacts downstream through Grand Canyon National Park.

Spring snowmelt runoff stored in Lake Powell is released throughout the remainder of the year, significantly increasing the river's discharge over the natural condition. The duration of a given discharge is the percent of time it is equalled or exceeded. The duration of daily mean stream flows recorded at the Lees Ferry gauge before and after the construction of Glen Canyon Dam is compared in Fig. 5. Reservoir storage has reduced the magnitude of relatively large, infrequent flows, those equalled or exceeded less than 10% of the time, by 50%. Release of stored snowmelt runoff during the remainder of the year has increased the magnitude of relatively common flows, those equalled or exceeded between 30 and 99% of the time. For example, the discharge equalled or exceeded 50% of the time since 1965 is 370 $m^3 s^{-1}$ compared to 230 $m^3 s^{-1}$ from 1922 to 1957, i.e. an increase of 60%. During unregulated, natural conditions, the ratio of the 10% exceedance flow to the 90% exceedance flow was 10.5, whereas, under regulated conditions, this ratio is only 3.4. The variability of daily mean flow has been greatly reduced.

The changes in the magnitude and frequency of stream flows in the Colorado River downstream from Glen Canyon are a direct and intended consequence. However, the existence and operation of Glen Canyon Dam had additional incidental, though

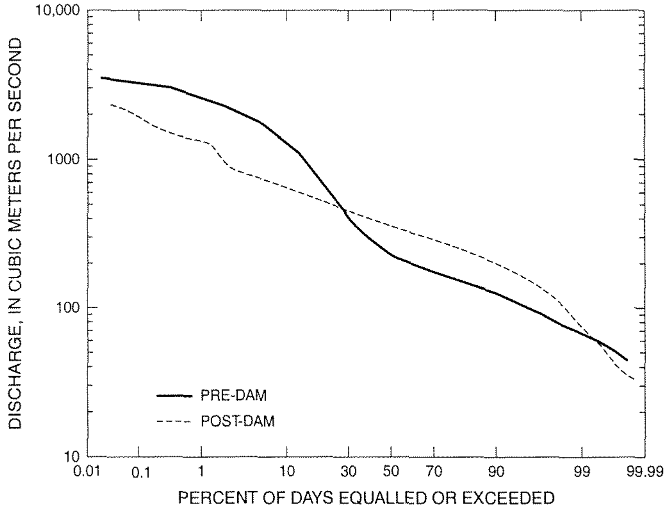

Fig. 5 Comparison of daily mean stream flow duration of the Colorado River at Lees Ferry before and after the construction of Glen Canyon Dam.

very significant, physical and ecological effects upon the Colorado River downstream through Grand Canyon National Park. Both the aquatic and riparian communities have been substantially altered by the invasion of exotic species more adapted to colder, clearer water and less variable flows than the native species (Turner & Karpiscak, 1980; Minckley, 1991). These issues and others are discussed extensively in Marzolf (1991).

Sediment transport

Prior to the construction of Glen Canyon Dam, the Colorado River carried a relatively large sediment load past Lees Ferry and through Grand Canyon. Daily sampling of the suspended sediment concentration began at the Lees Ferry gauge in November 1942, and at the Grand Canyon gauge, 150 km downstream, in October 1925. During the period 1942–1957, the mean annual suspended sediment load was 66×10^6 t at the Lees Ferry gauge and 86×10^6 t at the Grand Canyon gauge (Andrews, 1991). Approximately 20×10^6 t of sand, silt, and clay per year, on average, were supplied to the Colorado River between the Lees Ferry and Grand Canyon gauges. The suspended sediment concentration has also been sampled daily at gauges located at the two principal tributaries to this reach. These two tributaries, the Paria River and the Little Colorado River, represent 94% of the additional contributing drainage area and contribute approximately 75% of the suspended sediment supplied to the Colorado River between the Lees Ferry and Grand Canyon gauges (Andrews, 1991).

Glen Canyon Dam releases clear water. Virtually all sediment entering Lake Powell settles to the bottom and is deposited. Following closure of the bypass tunnels, fine sediment was scoured rapidly from the riverbed downstream. By 1970, the bed of the Colorado River from the dam downstream to the Paria River was armoured with coarse gravel and cobbles, which limited further degradation (Pemberton, 1976). Beginning with the Paria River, tributaries supply significant quantities of fine sediment to the Colorado and the annual sediment load increases downstream. The mean annual suspended sediment flux increases from approximately 5% pre-dam load downstream of the Paria to approximately 25% of the pre-dam load at the Grand Canyon gauge.

EROSION OF SAND BARS

When Congress authorized the construction of Glen Canyon Dam on 11 April 1956, less than 500 people had navigated the Colorado River through Grand Canyon by boat since J. W. Powell made the first trip in 1869. The popularity of whitewater boating increased dramatically during the following two decades. In the early 1970s, the National Park Service imposed a limit on the number of river runners of about 22 000 per year. Today, the economic value contributed by whitewater boating in Grand Canyon is about equal to and may exceed the value of electric power generated by Glen Canyon Dam (Bishop *et al.*, 1987). Increased visitation and use stimulated considerable interest and concern regarding the impacts of Glen Canyon Dam on the physical and ecological resources of Grand Canyon National Park. A particular concern was the erosion and loss of campsites along the river (Schmidt & Graf, 1990). Steep bedrock and talus form the banks of the Colorado River through most of Grand Canyon. Sand bars are nearly the only relatively flat campsites. These sand deposits typically occur along the channel margin where the flow separates from the river bank and creates a recirculating cell. Kearsley *et al.* (1994) identified 226 sand bars that were used as campsites within a reach of 365 km. Although sand bars are numerous, they are not particularly large or evenly distributed. Within certain reaches, the available campsites are limited and there is competition among river trips for desirable camps.

By the early 1970s, river runners, hydrologists, and other long-time observers of the Colorado River in Grand Canyon began to report the gradual loss of campsites through erosion of sand bars and the encroachment of thick stands of exotic vegetation. The basis for these reports was largely anecdotal and involved favourite or noteworthy campsites. Essentially no information concerning the number, size, and year-to-year variation of sand bars under the natural flow regime exists.

No comprehensive survey or description of the Colorado River was made prior to the construction of Glen Canyon Dam. The lack of detailed pre-dam information applies to nearly all physical and ecological aspects of the river corridor through Grand Canyon. The Lees Ferry and Grand Canyon gauging stations are notable exceptions. This lack of information has greatly hindered efforts to understand the effects of Glen Canyon Dam and devise alternative operating rules for the dam that would conserve and protect the aquatic and riparian resources of Grand Canyon National Park.

The first comprehensive study of sand bars in the Colorado River through Grand Canyon was conducted by Howard & Dolan (1979). Comparison of aerial and terrestrial photographs taken before and after the construction of Glen Canyon Dam revealed significant erosion of sand bars and encroachment of vegetation into areas previously scoured by the unregulated spring floods. Commonly, both the aerial extent and elevation of the bar tops had decreased substantially. Degradation of sand bars was greatest upstream of the Little Colorado River, however, the trend was pervasive throughout Grand Canyon. In addition to sand bar erosion, dense stands of mostly exotic vegetation became established at about the elevation of post-dam, regulated annual peak discharge (~920 $m^3 s^{-1}$) and approximately the elevation of the maximum power plant releases. The combined effects of erosion and vegetation encroachment substantially reduced the number and area of available campsites for river runners. Dolan *et al.* (1974) identified several factors leading to the loss of sand bars including (a) a decreased supply of sand from upstream, (b) a reduction in annual peak discharge, (c) large daily variations in flow that accelerate erosion, and (d) extensive human use.

In 1971, the National Park Service limited the number of river runners annually to reduce the human impacts along the river corridor, including the erosion of sand bars. The impacts of Glen Canyon Dam on sand bars was not addressed, however, until the Bureau of Reclamation (BOR) requested funds to refurbish and upgrade the power plant generators. Proposed modification to the generators would have increased the possible range of power plant releases. Responding to pressure from conservation and whitewater recreation groups, BOR initiated the Glen Canyon Environmental Studies (GCES) in 1983. Initially, GCES was a 3-year effort intended to address whether increasing the power plant capacity and the possible range of daily flow releases would accelerate the loss of sand bars. The scope and objective of the programme quickly expanded to encompass the broad range of resources and issues related to the operation of the Glen Canyon Dam power plant to meet peak electrical demand. Together, these studies are the most comprehensive and in-depth investigation of the effects of reservoir operation on a downstream physical and biological environment undertaken to date. A thorough discussion and review of these studies is presented in Marzolf (1991). The 1996 experimental flood concerned principally the relationship between sand bars and floods. The remainder of this paper discusses the analysis and observations that led to the flood hypothesis, and constraints upon future floods.

ORIGIN OF THE FLOOD HYPOTHESIS

With support from the GCES, several investigations concerning various aspects of sand bars were begun between 1983 and 1986. These investigations were formulated on the widely held assumption at the time that the Colorado River channel downstream from Glen Canyon Dam to the end of Grand Canyon was substantially depleted of sand relative to the pre-dam condition. It was assumed that the supply of sand from tributaries following closure of Glen Canyon Dam was significantly less than the amount of sand transported downstream by the regulated flows. Consequently, sand previously stored in the riverbed, and along the channel margins, had been scoured. Sand transport rate at a given discharge was believed to be gradually decreasing over time as a result of the progressive impoverishment of sand on the riverbed. This view was supported by the observed riverbed degradation immediately below the dam (Pemberton, 1976).

Large, daily fluctuations in flow (see Fig. 4) exacerbate the apparent sand deficit. The transport of sand observed at the Grand Canyon gauge varies with discharge to about the third power. Consequently, substantially more sand is transported through Grand Canyon to Lake Mead by larger daily fluctuations than would occur if the same volume of water were released at a constant rate. Assuming the 1922 Compact required minimum annual releases of 9.25×10^9 m^3 to satisfy the Upper Basin states obligation to deliver water to the Lower Basin states, Smillie *et al.* (1993) calculated that approximately four times as much sand would be transported annually by a daily regime of fluctuations from 140–710 m^3 s^{-1} than would be transported by a constant flow throughout the year of 322 m^3 s^{-1}. Accordingly, they concluded that reducing the range of daily fluctuations in discharge would decrease the amount of sand transported downstream annually and could possibly lead to an approximate balance between sand supply and transport.

Large daily fluctuations in discharge also accelerated erosion of sand bars. When the river stage rises a few metres, sand bars are submerged and river water fills the pores of the sand deposit. When the river stage subsequently falls, pore water flows out, and destabilizes the sand deposit. Sand slumps and liquefaction were commonly observed along the margins of sand bars following relatively rapid, large changes in river stage. Thus, limiting the range of daily fluctuations would also slow the erosion of sand bars, as well as achieving the balance between sand supply and transport. River management strategies to maintain sand bars focused primarily on two methods: (a) decreasing both daily and annual peak flows, in order to retain sand in the river channel, and (b) limiting the range of daily flow fluctuations in order to reduce sand bar erosion. As a result, in 1992, interim operating restrictions were imposed on the Glen Canyon Dam power plant pending completion of downstream river studies. The maximum release was reduced to 566 m^3 s^{-1}, nearly 25% below the power plant capacity. The objective of the change was primarily to reduce the annual load of sand transport through Grand Canyon. Furthermore, both hourly and daily maximum change in discharge were restricted. The maximum hourly change was set at 70.8 m^3 s^{-1} for increasing flows and 42.5 m^3 s^{-1} for decreasing flows. A maximum daily range was established from 141.6 to 226.6 m^3 s^{-1}, depending on the expected monthly volume of releases. The maximum hourly decrease, as well as the daily range, were established primarily to minimize the erosion of sand bars resulting from slumps and liquefaction associated with subsurface drainage. In practice, the limitation on the daily flow range was more restrictive on hydroelectric power generation than the maximum daily release. Exceptions to these restrictions were permitted under emergency conditions.

Several investigations were conducted to better understand the sand budget (tributary supply, channel storage, and transport) of the Colorado River through Grand Canyon. Reach-wise sand budgets were calculated for selected segments of the Colorado River using various assumptions. Although the uncertainty of these budgets was large, the several approaches led to similar conclusions. In one of the most extensive efforts, Randle *et al.* (1993) calculated annual sand budgets for the Colorado River from Lees Ferry to the Grand Canyon gauging station (09402500) during the post-dam period. They calculated that the supply of sand from tributaries exceeded downstream transport by approximately 25×10^6 t from 1965 to 1982. The unusually large river flows during the years 1983–1986 greatly increased downstream transport and removed a significant portion of the accumulated sand. Nevertheless, several million tons of additional sand were stored in the reach in 1986, two decades after the dam was completed. The rapid and pervasive erosion of sand bars from 1963 to 1982, following the closure of Glen Canyon Dam occurred while more sand was being supplied to the Colorado River than was being transported downstream. The loss of sand bars was not caused by an impoverishment of sand, as had been widely assumed.

A variety of possible future conditions, especially power plant operating regimes and sequence of annual basin runoff, have been investigated. In general, sand will accumulate in the channel so long as (a) daily peak releases do not frequently exceed 565 $m^3 s^{-1}$, (b) annual runoff is less than 12.5×10^9 m^3, and (c) long-term contribution of sand from tributaries remains constant (Randle *et al.*, 1993). Thus, given a limit on peak daily power plant releases, a neutral to slightly positive sand balance in the Colorado River downstream from the Paria is probable.

A Little Colorado River flood in February 1993, confirmed that a substantial quantity of sand had accumulated on the bed of the Colorado River even while sand bars were being eroded and removed along the channel margin. Approximately 48% of the sand bar campsites that existed following the high flows of 1984, had been removed by 1991 (Kearsley *et al.*, 1994). Remaining sand bars were substantially smaller than they had been in 1986. The February 1993 Little Colorado River flood more than doubled the discharge of the Colorado River below their confluence to about 990 $m^3 s^{-1}$ and contributed an estimated 4.2×10^6 t of sand (Wiele *et al.*, 1996). The accumulation of sediment on sand bars and in the channel within the first several kilometres downstream of the confluence was equal to the quantity of sand contributed by the Little Colorado River flood. However, a substantial thickness of sand, as much as 1 m, was deposited on sand bars as far as 250 km downstream. The total volume of sand deposited on bars throughout Grand Canyon greatly exceeded the volume of sand supplied to the Colorado River during the tributary flood. Therefore, most of the sand deposited on bars downstream from the mouth of the Little Colorado River must have been stored on the riverbed and entrained by the flood wave. The Little Colorado River flood demonstrated that a brief high flow would aggrade and reconstruct sand bars above the elevation of normal power plant releases. As a result, an experimental flood was proposed and discussed at a meeting of GCES scientists in September 1993.

CONSTRAINTS ON THE EXPERIMENTAL FLOOD

The proposal for an experimental flood to build and maintain sand bars in Grand Canyon raised a number of legal and economic issues as well as physical limitations. The principal constraints on the experimental flood and their resolution are summarized below.

Legal constraints

Colorado River reservoirs, including Glen Canyon Dam, are operated according to a series of legal documents, laws, court cases and treaties known collectively as the Law of the River (see Table 1). In 1916, the National Park Service Act created Grand Canyon National Park, through which the Colorado River flows, to be "unimpaired for the enjoyment of future generations". In 1922 the Colorado River Compact divided the waters of the Colorado River between the Upper Basin states and the Lower Basin states. The Upper Basin states were obligated to deliver 9.25 billion cubic metres (7.5 million acre feet) annually through the Compact Point, Lees Ferry, Arizona, for

Table 1 Law of the river.

	Purpose	Result
1922—Colorado River Compact		
Compact among seven states authorized by Act of Congress 19 August 1921	To provide for the equitable division and apportionment of the use of the waters of the Colorado River system	Apportions exclusive beneficial use of 7.5 million acre feet annually to each of the Upper and Lower Basins. Upper Basin states act as guarantor, they cannot reduce flow below 7.5 million acre feet per year in any consecutive ten year period. Upper Basin states shall not withhold and Lower Basin states shall not require water that cannot be put to domestic and agricultural use. Subject to the provisions of the Compact, water may be impounded and used for the generation of electrical power.
1928—Boulder Canyon Project Act (BCPA)		
Federal statute 43 U.S.C. 617 *et seq.*	To provide for controlling floods, improving navigation and regulating the flow of the Colorado River, providing for storage and for delivery of the stored waters thereof, for reclamation of public lands and other beneficial uses ... and for the generation of electrical energy ... to make the project self-supporting and solvent.	Provides for economic non-consumptive uses (flood control and hydropower). Authorized Hoover Dam and All American Canal. Before monies were appropriated for Hoover Dam, the Sec'y of the Interior was required to make provision for repayment of expenses, maintenance and investment within 50 years. Allocated 7.5 million acre feet among Lower Basin states (4.4×10^6 acre ft per year to California per the California Limitation Act, 300 000 acre ft per year to Nevada, 2.8×10^6 acre ft plus all of the Gila River to Arizona). The states never agreed to this division, but the litigation <u>Arizona v California</u> 373 US 546, 1963 resulted in this division.
1929—California Limitation Act		
California state statute	To resolve dispute as to division of Colorado River water among Lower Basin states.	California confirmed it would not take more than 4.4×10^6 acre ft per year and 50% of any excess above 7.5×10^6 acre ft per year. The balance of the 7.5×10^6 acre ft per year was to be divided among the other Lower Basin states.
1931—California Seven Party Agreement		
California and local water users in California	To resolve dispute as to division of Colorado River water within California.	Allocated 4.4×10^6 acre ft per year of water among California water users. Department of Interior entered into water delivery contracts with entities.
1940—Boulder Canyon Project Adjustment Act		
Federal statute 54 Stat. 774 19 July 1940	To provide for required repayment of dam construction in 50 years—on 1 June 1987.	Revised rates for electricity. No person shall have the right to stored water except by contract with the Secretary of the Interior.
1944—Mexican Water Treaty		
US and Mexico effective 8 November 1945	To satisfy Mexico claim to Colorado River water.	Confirmed US obligation to provide 1.5×10^6 acre feet annually to Mexico. In a drought, Mexico use is decreased in the same proportion as the US created a boundary and water commission to resolve disputes.
1948—Upper Colorado River Basin Compact		
Upper Basin states: Colorado, Utah, Wyoming and New Mexico	To divide Colorado River water among Upper Basin states.	Established Upper Colorado River commission—one member from each state plus one named by the US President. Apportioned 7.5×10^6 acre feet among Upper Basin states in the following percentages: Colorado 51.75%, New Mexico 11.25%, Utah 23%, and Wyoming 14%. Some apportionment was necessary before water projects could be developed in the Upper Basin states.

Table 1 *continued*

	Purpose	Result
1956—Colorado River Storage Project (CRSP) Act		
Federal statute 43 U.S.C. 620 *et seq.*	Initiates the comprehensive development of the water resources of the Upper Colorado River Basin, for the purposes, among others, of regulating the flow of the Colorado River, storing water for beneficial consumptive use, making it possible for the States of the Upper Basin to utilize the waters, providing for the reclamation of arid and semiarid land, for the control of floods and for the generation of hydroelectric power as an incident of the foregoing purposes.	Authorizes Glen Canyon Dam and other Upper Basin projects. Created the Upper Colorado River Basin Fund which collects monies and pays operating, maintenance and replacement costs of the projects. Section 7 of the Act provides that the hydroelectric plants authorized shall be operated so as to produce the greatest practicable amount of power that can be sold at firm rates, but the Secretary shall not interfere with the Colorado River Compact, the Boulder Canyon Project Act, the Upper Colorado River Basin Compact and the Boulder Canyon Project Adjustment Act, nor any contracts lawfully entered into under said Acts.
1963—Arizona v. California		
US Supreme Court decision in lawsuit between states 373 US 546 (1963)	To resolve claims by states and tribes to Colorado River water by interpreting Boulder Canyon Project Act.	Confirmed Act allocated Colorado River Water among Lower Basin states. Also specifically recognized reserved water rights held by tribes living on reservations along the Colorado River. Decision confirmed dependable supply of water necessary for commitment to build the Central Arizona Project. Also, upheld Winters doctrine—that the federal government intended to reserve water to tribes on reservations for practicably irrigable land.
1968—Colorado River Basin Project Act		
Federal statute 43 U.S.C. 1501 *et seq.*	To provide for further comprehensive development of the water resources of the Colorado River Basin and for provision of additional and adequate water supplies in the Upper and Lower Basins. For the purposes, among others, of regulating the flow of the Colorado River; controlling floods; improving navigation; providing for the storage and delivery of the waters of the Colorado River for reclamation of lands including supplemental water supplies, and for municipal, industrial, and other beneficial purposes; improving water quality; providing for basic public outdoor recreation facilities; improving conditions for fish and wildlife and the generation and sale of electrical power as an incident to the foregoing purposes.	First emergence of water quality, including improving conditions for fish and wildlife, as a purpose of water projects. Authorized construction of the Central Arizona Project and smaller Upper Basin projects. §602 of the act provided for "Operating Criteria" to be developed by the Secretary of the Department of the Interior, in consultation with the seven basin states and parties to water contracts with the US. The criteria are to make provision for storage and releases in the following priority: (1) to supply half of any deficiency under the obligation to provide Mexico 1.5×10^6 acre ft per year, (2) releases to comply with the obligation to provide 7.5×10^6 acre ft per year to the Lower Basin under the 1922 Compact, (3) storage to assure deliveries described above, without impairment of the Upper Basin annual consumptive uses provided water not required to be stored shall be released: (a) to the extent the water can be used by the Lower Basin, but no releases if active storage in Lake Powell is less than that in Lake Mead, (b) to maintain equal active storage, and (c) to avoid anticipated spills from Lake Powell.
1973—Endangered Species Act		
Federal statute 16 U.S.C. 1531 *et seq.*	To provide a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved. To confirm the policy of Congress that federal agencies shall cooperate with state and local agencies to resolve water resource issues in concert with conservation of endangered species.	Development of special programmes intended to protect listed species in the basin while allowing historical and new consumptive uses to occur. Legal duty to recover endangered native fish species on the Colorado Plateau.

Table 1 *continued*

	Purpose	Result
1969—National Environmental Policy Act		
Federal statute 42 U.S.C. 4321 *et seq.*	To reorder processes by which Federal Government makes decisions which have significant environmental impacts.	Requires federal agencies to precede any major federal action significantly affecting the quality of the human environment with an identification of all potential environmental impacts, and identification of all practical alternatives to the proposed action and identification of a preferred course of action.
1972—Clean Water Act		
Federal statute 33 U.S.C. 1311 *et seq.*	To restore and maintain the chemical, physical, and biological integrity of the nation's waters.	Requires water quality standards be set for all waters of the United States.
1973—Minute 242		
International Boundary and Water Commission	To satisfy the US obligation to provide water to Mexico at certain salinity concentrations.	Water quality standards for salinity set at three locations in the Lower Basin.
US and Mexico		
1974—Colorado River Basin Salinity Control Act		
Federal statute 43 U.S.C. 1591 *et seq.*	To authorize Colorado River Salinity Control Advisory Council.	Desalter and salinity control funded from hydropower revenues—predicated on protection of consumptive uses.
1977—Western Area Power Administration (WAPA)		
Department of Energy Organization Act of 1977 42 U.S.C. 7102	To administer the sale of electricity from Bureau of Reclamation hydropower facilities in the Colorado River Basin.	Resolves potentially conflicting interpretations of Law of the River such as BCPA which provides hydropower revenues that are incidental to other uses, and CRSP Act which directs operation of hydropower to produce greatest practicable amount of power, by administrative decisions.
1992—Grand Canyon Protection Act		
Federal statute 12 U.S.C. 1202	To elevate the recreational and environmental values of the Grand Canyon in relation to the operation of Glen Canyon Dam for hydroelectric purposes. Authorizes the Secretary to operate Glen Canyon Dam in such a manner as to protect, mitigate adverse impacts to, and improve the values for which Grand Canyon National Park and Glen Canyon National Recreation Area were established, including, but not limited to, natural and cultural resources and visitor use.	Reallocated the costs of construction, operation, maintenance, replacement and emergency expenditures for Glen Canyon Dam. Allocated costs of operations: operations for the purposes established in CRSP are reimbursable, while operations for the purposes established in Sec. 1202 of the Act, are not reimbursable from hydropower revenues.

the benefit and use of the Lower Basin states. In 1956 the Colorado River Storage Project Act authorized Glen Canyon Dam and other water projects making it possible for the Upper Basin states to develop Colorado River water for their beneficial use consistent with their Compact obligations. In 1968 Congress passed the Colorado River Basin Project Act which authorized annual operating criteria to include a storage volume to protect the Upper Basin states from shortages and avoidance of unnecessary spills from Glen Canyon Dam. Lastly, the Grand Canyon Protection Act of 1992 was passed to protect, mitigate damage to, and improve the values of Grand Canyon National Park. This Act directed the Secretary of the Department of the Interior to prepare an Environmental Impact Statement on the operation of Glen Canyon Dam and adopt criteria directed to the ecological health of the Grand Canyon.

When an experimental flood was proposed to build sand bars, a conflict arose between the Upper Basin states and power consumers, and environmentalists. In the 1956 Act, Congress directed the Department of the Interior to operate Glen Canyon Dam "so as to produce the greatest practicable amount of power and energy that can be sold at firm rates" (Section 7). The Upper Basin states and power consumers believed this language in the 1956 Act prohibited spills in excess of power plant capacity, except as required by dam safety considerations. Others believed that the "greatest practicable" directive was not limited by only dam safety. They argued that other federal objectives and resources, including especially the protection of Grand Canyon National Park, would justify releases from Glen Canyon Dam in excess of power plant capacity. Opposition to the experimental flood by the Upper Basin states and power consumers was not based on the consequences of a one-time event. Rather, the Upper Basin states and power consumers were concerned that the experimental flood would set a precedent for allowing flows in excess of power plant capacity for environmental purposes.

A compromise was eventually reached which allowed the experimental flood to occur, and then, if successful, would establish the basis for future sand bar building releases. The soon-to-be-completed Environmental Impact Statement on Glen Canyon Dam Operations provided the special circumstances under which an experimental release in excess of the power plant capacity could occur without establishing a precedent. The several parties agreed that subsequent releases in excess of power plant capacity for the purpose of rebuilding sand bars would occur only when the available reservoir storage and forecast runoff were sufficient to make a spill probable. This agreement allowed the Upper Basin states and power consumers to protect and limit the purposes of Glen Canyon Dam to provide for Upper Basin water development and power production while enabling environmentalists and recreationists to manage the timing and magnitude of spills for environmental purposes.

Economic constraints

Glen Canyon Dam was built in order to provide the Upper Basin states with a means to comply with the Law of the River, delivering water on an annual basis to the Lower Basin states, while developing its own water resources. As an additional benefit, hydroelectric revenues could be used to finance delivery of water throughout the basin, through authorized irrigation, municipal and industrial supply projects (Ingram *et al.*, 1991). Without subsidies from Glen Canyon Dam operations, these regional reclamation projects would not have been built, nor could they continue operations (Ken Maxey, personal communication, 1999). Since 1980, when Lake Powell filled for the first time, gross hydropower revenues from Glen Canyon Dam have averaged approximately US$63 million annually.

The Colorado River Storage Project Act listed hydropower as an incidental purpose, superseded by the primary purposes of beneficial water use, reclamation and flood control, in order to ensure power production would not conflict with the Law of the River. In practice, maximizing power production and providing adequate water deliveries have not conflicted, as power production depends upon hourly and daily fluctuations in discharge while consumptive use is on a longer time scale (National Research Council, 1996). As a result, Glen Canyon Dam has been operated to maximize power revenues and consequently any change in operation will result in decreased revenues from power production. Hydropower revenues are used to repay the costs of construction, operation and maintenance of all facilities of the Colorado River Storage Project (CRSP) and environmental projects such as GCES and the Endangered Fish Programme for the Upper Colorado River.

The price of power from Glen Canyon is calculated to ensure that revenues are sufficient to repay all costs assigned under the 1968 Act. If less hydropower is produced, while the same revenues are required, then the unit cost of power must increase to generate the same revenues. Consequently, one might believe that the cost of the 1996 flood, and the loss in hydropower revenues, was being born disproportionately by consumers of Glen Canyon Dam power through higher power costs. While this may be true for the 1996 flood, in the case of subsequent sand bar building floods, the 1992 Act requires costs of the dam from 1998 forward to be reallocated between old purposes, which are: reclamation, water deliveries, flood control and power and new purposes: to protect, mitigate damage to, and improve values of Grand Canyon National Park (Section 1804(e)). The latter purposes are non-reimbursable and therefore are paid by the US Treasury through decreasing the principal to be repaid by CRSP and Glen Canyon Dam power. Consequently, the costs of sand bar building flood flows will not have to be recovered from the sale of Glen Canyon Dam power from 1998 forward, and therefore such flows will not increase the costs of Glen Canyon Dam power to its customers.

The cost of the 1996 experimental flood should also be put in perspective. The total cost of the 1996 experimental flood in terms of lost hydropower revenues was approximately US$2.5 million, resulting in a reduction in the economic value of the hydropower generated at Glen Canyon Dam in 1996 by 3.3% (Harpman, 1997). The economic cost of releasing water in excess of power plant capacity, approximately 268×10^6 m^3, was US$1.3 million. The additional cost arose from adjustments made in the months following the flood to reduce the risk of an uncontrolled spill that would have compromised the experiment. In contrast, the value of rafting through Grand Canyon and associated tourism revenues, which is dependent on the continued existence of the sand bars, is approximately US$80 million annually.

Physical constraints

The Colorado River Compact requires that the states of the Upper Colorado River Basin permit an average annual volume of 9.25×10^9 m^3 s^{-1} to flow past the Compact

Point. The instantaneous discharge is not important, only the annual volume. Thus, all flow released from Glen Canyon Dam during the experimental flood is credited to the Upper Basin states. The maximum discharge through the Glen Canyon power plant is approximately 860–935 $m^3 s^{-1}$, depending on the reservoir surface elevation. Any flow released from Glen Canyon Dam in excess of power plant capacity does not generate electrical energy, and potential revenues are lost. An economically efficient flood will deposit the greatest amount of sand on bars with the least volume of water released in excess of power plant capacity.

As described by Andrews *et al.* (1999), the rate of sand deposition in an eddy varies with about the fourth power of the river discharge. Consequently, for a given volume of water released from the dam, a larger flood will deposit more sand in eddies in a proportionally shorter time than will a smaller flood. Thus, a short, large flood will deposit sand and reconstruct sand bar campsites more economically than a long, small flood.

Water can be released from Glen Canyon Dam by two means other than the power plant: (a) four hollow jet tubes with a combined discharge of about 425 $m^3 s^{-1}$ and (b) a spillway tunnel with an intended capacity of nearly 6000 $m^3 s^{-1}$. The spillway tunnel, however, failed when passing a discharge of about 1500 $m^3 s^{-1}$ in June 1983. Although redesigned and repaired, the BOR was reluctant to release large discharges through the spillway tunnel. Furthermore, a larger river discharge will tend to deposit sand and build bars to a higher elevation than will a smaller discharge, other factors being equal. Sand bar campsites standing too high above the normal river stages are less desirable. For these reasons, the flood magnitude was set at 1 275 $m^3 s^{-1}$, approximately the combined maximum discharge of the power plant and hollow jet tubes.

Theoretical calculation, using estimated river suspended-sand concentrations and rates of water exchange between the river and eddies, indicated that the average sand deposition rate in a typical eddy would be 5–10 cm day^{-1}. Thus, it was anticipated that several days would be required to deposit a sufficient thickness of sand to be confidently measured. A weeklong flood seemed to many GCES scientists to be the minimum duration needed to test the flood hypothesis.

RESULTS OF THE EXPERIMENTAL FLOOD

The experimental flood was conducted between 23 March and 7 April 1996. The flood hydrograph is shown in Fig. 6. Normal power plant operations ceased at midnight on 23 March and the released discharge was reduced to 225 $m^3 s^{-1}$. The discharge was held constant for three days to provide the opportunity to survey the sand bars and other river resources immediately before the flood. Beginning at 3:00 a.m. on 26 March the discharge increased to 1275 $m^3 s^{-1}$ over a period of 10 hours. The flood discharge was held constant until noon on 2 April just over 7 days. Following the flood, the discharge was again reduced to 225 $m^3 s^{-1}$, and held constant for 3 days to provide for a survey of the geomorphic, aquatic and riparian resources. Normal power plant operations resumed after midnight on 8 April.

Collier *et al.* (1997) summarize the flood's effects on the physical and biological resources of the Colorado River. An extensive description and analysis of the many geomorphic, aquatic and riparian impacts of the experimental flood will be found in Webb *et al.* (1999). The experimental flood was effective in achieving its primary

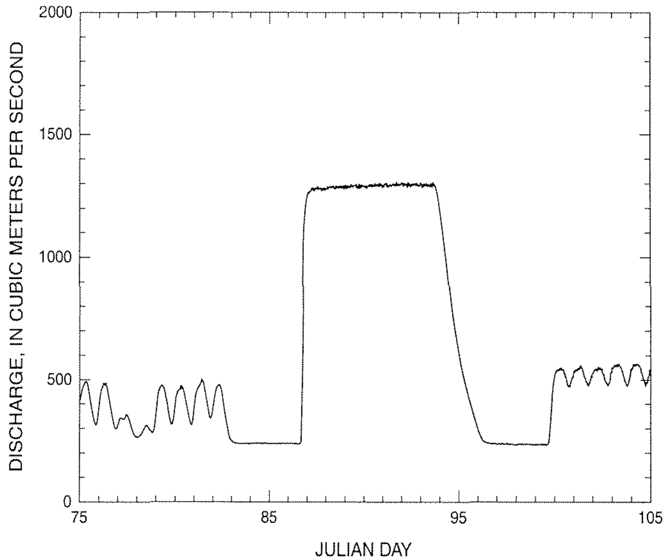

Fig. 6 Hydrograph of the 1996 experimental flood recorded at the Colorado River at Lees Ferry, Arizona, gauge.

objective: rebuilding sand bars. Large volumes of material deposited rapidly during the first several hours of the flood (Andrews *et al.*, 1999). As much as 3.5 m of sand were deposited over the crest of some bars within the first 24 h. Daily bathymetric resurveys of selected eddies showed relatively large volumes of sand, typically a few to several thousand cubic metres, were eroded and deposited from one day to the next. Large subaqueous mass failures of over steepened parts of the sand bar occurred in all eddies. In general, deposition over the crest of the sand bar was approximately balanced by erosion along outer margins of the sand bar. As a result, the exposed area of the majority of sand bars, the area commonly used by river runners, had increased appreciably following the flood.

As noted above, a substantially decreased annual maximum discharge and a power plant regime to meet daily peak demand have affected the river channel, aquatic organisms, and riparian vegetation in numerous ways. The experimental flood had a lesser impact on these elements of the river corridor than it did for sand bars, as had been expected. The experimental flood was approximately half of the pre-dam annual flood. Debris fans deposited by tributaries in the Colorado River channel were eroded to a limited degree (Webb *et al.*, 1999). Dense stands of exotic riparian vegetation that were established near the elevation of peak power plant releases were inundated, but not extensively disturbed by the flood (Kearsley & Ayers, 1999). Similarly, populations of exotic fishes that have become established in the absence of large annual floods appeared to be unaffected by the experimental flood (Valdez *et al.*, 1999).

FUTURE CONTROLLED FLOODS

An operating plan is developed annually for operation of Colorado River reservoirs including Glen Canyon Dam. The plan is developed in accord with the Colorado River

Basin Project Act of 1968 and the Criteria for Coordinated Long-Range Operation of Colorado River Reservoirs authorized by that Act. In addition, the plan must comply with Operating Criteria for Glen Canyon Dam in accordance with the Grand Canyon Protection Act of 1992 (see Table 1). The operating plan is developed after consultation with the representatives of the governors of the seven basin states, the Upper Colorado River Commission, appropriate federal agencies, representatives of the academic and scientific communities, environmental organizations and the recreation industry, contractors for federal power, and others interested in Colorado River operations. The operating plan is developed with "appropriate consideration of the uses of the reservoirs for all purposes, including flood control, recreation, enhancement of fish and wildlife, and other environmental factors" (Operating Criteria, Article I(2)).

Following the success of the experimental flood in rebuilding sand bars along the Colorado River through Grand Canyon, the Department of the Interior concluded that the operating criteria for Glen Canyon Dam would include occasional releases greater than power plant capacity. The releases are to be managed to the maximum extent possible to (a) protect river sediment storage downstream, or (b) be released in such a way as to reshape river topography, redeposit sediment and enhance aquatic habitat, (US Bureau of Reclamation, 1996). Furthermore, such releases would occur during years when an uncontrolled spill was likely. The specific hydrological conditions under which a bar building release would occur were determined by the representatives of the several parties that are consulted for the Annual Operating Plan. The risk of an uncontrolled spill is determined by simulating various alternative forecast basin runoff and reservoir operating regimes. It was agreed that future releases in excess of the power plant capacity will occur when the 1 January forecast basin runoff exceeds 140% of the mean inflow to the reservoir. Basin runoff forecasts are updated twice a month throughout the January–July period. Monthly water releases from Glen Canyon Dam are revised based upon these updated forecasts and available reservoir volume. A release in excess of the power plant capacity also, will occur whenever the projected monthly release exceeds 1.85×10^9 m^3, which is equivalent to a mean outflow of about 700 m^3 s^{-1}. Under these conditions future bar building releases will occur about one year out of six. Finally, because the goal is to improve the physical, biological, cultural and recreational resources along the Colorado River through Grand Canyon National Park, the environmental costs and benefits of any future release in excess of power plant capacity will be considered. A monitoring and research programme has been implemented and will continue to measure the effect of operating criteria on downstream resources (Annual Operating Plan for Colorado River Reservoirs, 1998—Jayne Harkins, Chair Colorado River Management Work Group).

CONCLUSION

Impoundment of the Colorado River and the demand for its water for conflicting uses presented a problem that is common to other regulated rivers. While the impoundment and operations generally satisfy traditional water resource needs, these same operations negatively impact environmental uses and values. In addition, Glen Canyon Dam involved hydropower revenues that supported other projects and many power users dependent upon its lower priced and readily available power. Glen Canyon Dam also controls the flow of a river that is the subject of complex laws and treaties developed over more than 70 years.

The identification of unintended consequences of regulation and current operations was the first step in accommodating water distribution and power needs with environmental values. The scientific studies of these consequences resulted in identification of an experimental flood as a means to enhance environmental values negatively impacted by the dam and its operations. But in addition, the experimental flood had to surmount legal, economic and physical constraints. The experimental flood of 1996 is a model of the type of scientific investigation and satisfaction of legal, economic and physical constraints that will be required in the future for satisfaction of the competing values of our water resources.

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