Journal of Environmental Management (2001) **63**, 307–324
doi:10.1006/jema.2001.0494, available online at http://www.idealibrary.com on IDEAL®

Climate extremes and adaptive management on the Colorado River: Lessons from the 1997–1998 ENSO event

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Received 13 July 1999; accepted 26 June 2001

The Colorado River system exhibits the characteristics of a heavily over-allocated or 'closing water system'. In such systems, development of mechanisms to allow resource users to acknowledge interdependence and to engage in negotiations and agreements becomes necessary. Recently, after a decade of deliberations and environmental assessments, the Glen Canyon Dam Adaptive Management Program (GCDAMP) was established to monitor and analyze the effects of dam operations on the Grand Canyon ecosystem and recommend adjustments intended to preserve and enhance downstream physical, cultural and environmental values. The Glen Canyon Dam effectively separates the Colorado into its lower and upper basins. Dam operations and adaptive management decisions are strongly influenced by variations in regional climate. This paper focuses on the management of extreme climatic events within the Glen and Grand Canyon Region of the Colorado River. It illustrates how past events (both societal and physical) condition management flexibility and receptivity to new information. The types of climatic information and their appropriate entry points in the annual cycle of information gathering and decision-making (the 'hydro-climatic decision calendar') for dam operations and the adaptive management program are identified. The study then describes how the recently implemented program, lessons from past events, and new climate information on the Colorado River Basin, facilitated responses during the major El Niño–Southern Oscillation (ENSO) event of 1997–1998. Recommendations are made for engaging researchers and practitioners in the effective use of climatic information in similar settings where the decision stakes are complex and the system uncertainty is large.

Keywords: climatic extremes, adaptive management, Colorado River, El Niño–Southern Oscillation, water resources, decision calendar, focusing events.

Introduction

The history of the Colorado River Basin is one of rapidly changing social dynamics and pressures, including increasing population and consumption, water diversions and dam building, deteriorating water quality, changes in environmental and aesthetic values, variations in state laws and, evolving federal, state, tribal, and local interactions (WWPC, 1998). It is also a history of varying and changing physical and ecological conditions that control regional climate, hydrology, and geomorphology. These cumulative pressures have resulted in a limited regional capacity to implement plans for responding to environmental variability and change. The situation has however, recently shown promising signs of improvement.

At present, the Colorado River (Figure 1) exhibits the characteristics of a 'closed or closing' water system (see Peabody, 1991). In such systems,

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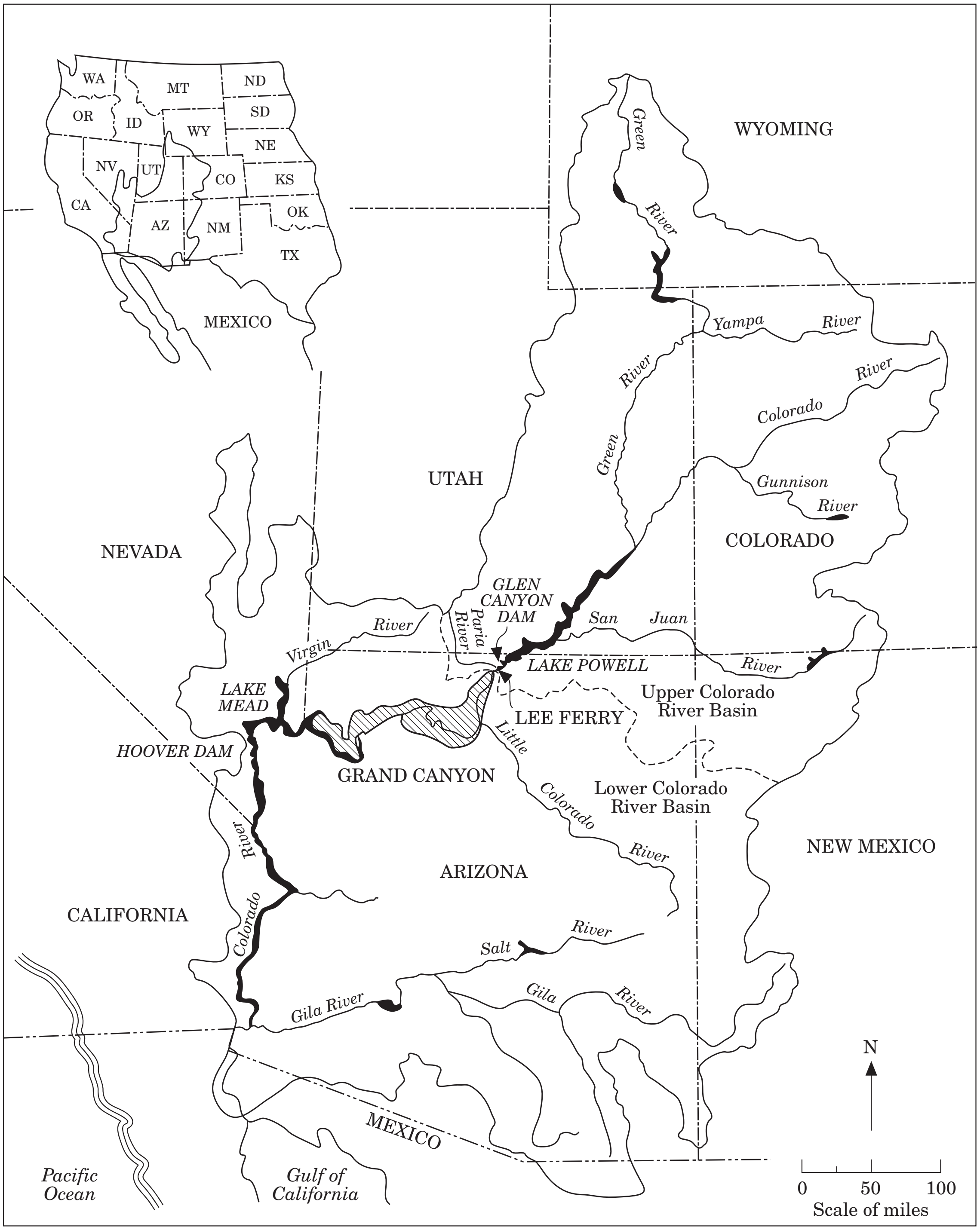

Figure 1. The Colorado River Basin (adapted with permission from DOI, 1995).

management of interdependence becomes a public function, and the development of mechanisms to allow resource users to acknowledge interdependence and to engage in negotiations and binding agreements on resource allocation become increasingly necessary. In April 1996, after ten years of deliberations and environmental impact assessments, the first experimental 'high flow' to enhance downstream resources in the Grand Canyon was released from Glen Canyon Dam (Webb *et al.*, 1999). This event marked a 'dramatic physical start' for an even broader Adaptive Management Program (National Research Council, 1999a).

In October 1996, the Secretary of the US Department of the Interior signed the Record of Decision (ROD) establishing the Glen Canyon Dam Adaptive Management Program (hereafter GCDAMP; also see list of acronyms in Appendix). The GCDAMP provides a process for incorporating scientific information and recommendations from a diverse group of stakeholders (see next section) in the evaluation and management of dam operations for the benefit of downstream resources, as well as for water supply and hydropower. The GCDAMP is composed of three equally balanced elements: (1) a technical process, including the Grand Canyon Monitoring and Research Center (GCMRC), the advisory Technical Working Group (TWG) and external peer review; (2) an administrative coordination process that is headed by the Secretary's designee, and (3) a decision process for making recommendations to the Secretary through his/her designee on the Adaptive Management Working Group (AMWG). This process parallels the decision sequences that determine the Annual Operating Plan (AOP) for the entire Upper Basin. Both of these processes are discussed further below. The present study focuses on the management and use of information on climatic risks and uncertainties in this multi-actor setting. It discusses the responses to past events (both social and environmental) as important factors influencing present management flexibility and receptivity to new information. Emphasis is placed on responses during the 1997–1998 El Niño–Southern Oscillation (ENSO) event.

ENSO events are the coupled anomalous oceanic warming (El Niño) and atmospheric response (Southern Oscillation) of the central and eastern tropical Pacific, known to affect climate worldwide (see Glantz, 1998). Major international interest in the causes, monitoring and forecasting of these events, and their impacts, has developed since the 'ENSO event of the century' in 1982–1983. This event caught most of the climate research community by surprise. This study describes how recently implemented resource management approaches, lessons from past events, and new ENSO-related climate information on the Colorado River Basin, facilitated effective responses during the 1997–1998 event (the second 'ENSO event of the century'). 'Effective response' is taken here to mean enabling the array of complementary actions that allows the system to meet agreed -upon seasonal and long-term physical, ecological, cultural, water resources, and hydropower needs.

The paper is structured as follows. It begins by describing the changing management environment of the Colorado River in the Glen Canyon and Grand Canyon Region. A discussion of the two major interacting planning processes (development of the AOP for the Colorado River and planning for experimental releases from Glen Canyon Dam) then follows. Within this setting, the types of climatic information and their appropriate entry points in the annual cycle of information gathering and decision-making (the 'hydro-climatic decision calendar') are identified. A climatological analysis of significant extreme events in the years since the completion of Glen Canyon Dam is then presented. Actions during the 1997–1998 ENSO event are described, in the context of these past events and tradeoffs among different stakeholder groups involved in the GCDAMP. Finally, recommendations are made for engaging researchers and practitioners in joint studies of the effective use of climatic information in multi-actor settings.

The study represents one of the few cases documenting the use of climate information throughout the life-cycle of a major ENSO event (see National Research Council, 1999b), and in which the researchers involved were accepted as both participants and observers in the course of the event. The second author (T. S. M.) is one of the few individuals who has been actively involved in the Glen Canyon Dam Adaptive Management Program since its developmental research phase as the Glen Canyon Environmental Studies program began in 1986 (see Webb *et al.*, 1999).

Data and approaches

The data employed in this study include the results of open-ended interviews, analyses of climatic and hydrological data and model runs, and historical and institutional analyses of water and environmental management in the basin. The climatic data included analyses of stream-flow and precipitation records in major sub-basins of the Upper Colorado, monthly atmospheric circulation maps through the lifecycles of previous ENSO events and for present conditions, temperature data at different elevations and, the National Oceanic and Atmospheric Administration (NOAA) climate forecast for the region. Special effort was made to evaluate and highlight differences between the impacts of past climatic events. The authors participated in several planning and decision-making meetings carried out by the GCMRC under the auspices of the AMWG.

Presentations to the AMWG and TWG were made throughout the course of the ENSO event.

The 32 interviewees for this part of the study consisted of the members of the AMWG, TWG, and GCMRC acting in each of the three elements outlined above (Table 1). It should be noted that this list does not encompass the entire spectrum of *potential* stakeholders. Personnel with responsibilities for stream-flow forecasts at the National Weather Service's River Forecast Center and Operations of Glen Canyon Dam at the Bureau of Reclamation (BOR) were also interviewed and included in discussions between September 1997 and July 1998.

The barriers to climate information acceptability and use reflect combinations of technical, cognitive, financial, institutional, and cultural conditions that influence the processes of information generation, content, dissemination, communication, utilization and evaluation (Pulwarty and Redmond, 1997). An explicit attempt was made in this study to, (1) address barriers to the use of climate information including forecasts, as identified in previous studies, and (2) identify climate-sensitive activities and appropriate entry-points for climatic information throughout the year, i.e. through 'the calendar of information gathering and decision-making'. This paper draws on sections of the above interviews that have direct bearing on activities involving Glen Canyon Dam operation during the 1997–1998 ENSO event. It forms part of a more comprehensive project on adaptive management in the Colorado River Basin (Pulwarty and Melis, in prep.).

Table 1. Agencies and organizations participating in interviews

(1) Cooperating Federal and State agencies involved in preparing the final Environmental Impact Statement on Operations at Glen Canyon Dam (DOI, 1995), and having management jurisdiction in the affected areas including the Bureau of Reclamation, Bureau of Indian Affairs, US Fish and Wildlife Service, National Park Service, Western Area Power Administration, Arizona Department of Game and Fish, and the Upper Colorado River Basin Commission.
(2) Six Native American Tribes: Hopi Tribe, Hualapai Tribe, Dine (Navajo) Nation, San Juan Paiute Tribe, Southern Paiute Consortium, Pueblo of Zuni.
(3) Water Resources Departments from the seven Colorado River Basin states: Arizona, California, Colorado, Nevada, New Mexico, Wyoming and Utah.
(4) Environmental groups, recreation interests, and contractors who purchase Federal power from Glen Canyon Dam through the Department of Energy, including American Rivers, Grand Canyon Trust, Grand Canyon River Guides Association, Trout Unlimited, and the Colorado River Energy Distribution Association.

The changing environments of the Glen and Grand Canyon Region

The Glen Canyon Dam (henceforth GCD) was completed in 1963, effectively dividing the Colorado River into its Upper and Lower Basins. The Upper Basin provides 80–90% of the total flow in the Colorado. The primary role of the GCD is to enable the Upper basin states of Utah, Colorado, Wyoming and New Mexico to utilize their apportionment of Colorado River water, while meeting obligations for water delivery to the Lower Basin states of Arizona, California, and Nevada. These activities are carried out consistent with the laws, treaties, compacts, and court decisions regarding Colorado River operations, collectively known as the Law of the River.

On average, the main branch of the Colorado flowing out the west slope of the Colorado Rockies, the Green River flowing south out of Wyoming and, the San Juan River flowing out of southwestern Colorado, respectively contribute about 42, 42 and 16% of the annual flow into Lake Powell behind GCD. Flow into Lake Powell consists of about 50%-unregulated input, and 50% subject to operations at other upper basin reservoirs. Decadal-scale climatic factors influencing present water allocations have been discussed in greater detail elsewhere (Stockton and Jacoby, 1976). Briefly, the period 1905–1930 was the wettest such period in 400 years of record, with 19·8 billion cubic meters per year (i.e. a gigacubic meter per year, hereafter $\mathrm{Gm^3yr^{-1}}$) estimated annual average flow at Lee Ferry (see Figure 2). The Colorado River Compact created in 1922 among the seven basin states used this average as the base minimum for fixed allocation between Upper and Lower Basins. Since the signing of the Compact the estimated annual virgin flow (1922–1997) has been 17·7 $\mathrm{Gm^3yr^{-1}}$. Under the Compact, Lower Basin states have firm rights to this allotment. During the Dust Bowl years of the 1930s, streamflow averaged 12·6 $\mathrm{Gm^3yr^{-1}}$, with an historic low of 6·9 $\mathrm{Gm^3yr^{-1}}$ in 1934 (Figure 2). Under similar future conditions, if the Upper Colorado River Basin states were to consume their allocation of 9·3 $\mathrm{Gm^3yr^{-1}}$ then their legal obligation to the Lower Basin would be in default. The engineering solution to this problem was to construct a dam (the GCD) above Lee Ferry that could provide storage to meet downstream

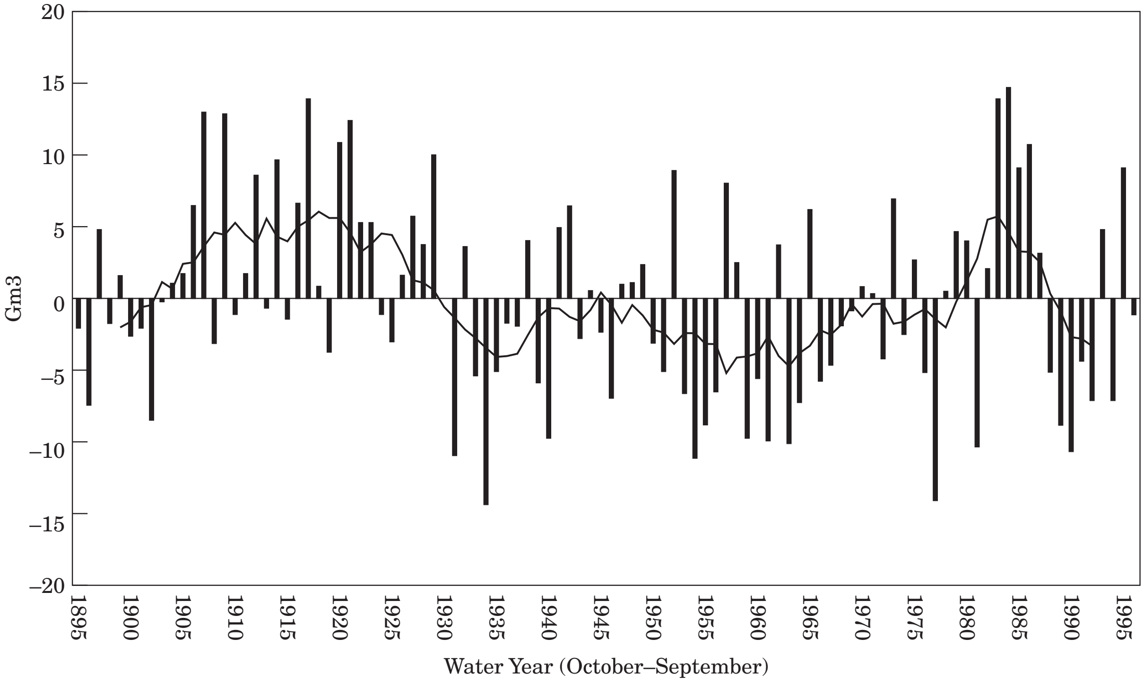

Figure 2. Colorado River streamflow at Lee Ferry, Arizona for Water Years 1895–1996: Annual deviations from long-term mean and 9-year moving average.

allotments during dry years while providing water for irrigation and development in the Upper Basin.

Maintaining geopolitical equity between basins was the major purpose served by the GCD (Ingram *et al.*, 1990). The planning process focused on balancing water supply and flood control requirements but did not address environmental issues (see Hughes, 1991, and next section). Power generation itself was second to the need to generate revenue for other water projects primarily in the Upper Basin. More recently, major changes in GCD operations have resulted from increasing concerns regarding downstream ecosystem resources. Management objectives are now organized under nine 'resource' areas identified in the GCD Environmental Impact Statement: water, sediment, fish, vegetation, wildlife and habitat, endangered and other special status species, cultural resources, recreation, and hydropower (National Research Council, 1999a). Thus, decisions in the Colorado River Basin at GCD and the Grand Canyon involve actions and consequences that cross many temporal and spatial scales (Table 2). These concerns are reflected in the Grand Canyon Protection Act 1992 which required the Secretary to implement 'interim operating criteria' for the operation of Glen Canyon Dam in order to protect downstream resources in Grand Canyon National Park and to complete an environmental impact analysis and establish long-term monitoring of dam operations under the National Environmental Policy Act 1969. The mechanism for implementing this program in full view of these complexities rests with the Glen Canyon Adaptive Management Program.

Table 2. Examples of cross-scale issues in river management in the Glen and Grand Canyons

TEMPORAL SCALES

Indeterminate: Flows necessary to protect endangered species

Long-term: Inter-basin allocations and those allocations among basin states

Decade: Upper Basin delivery obligations, life cycle of humpback chub (*Gila cypha*)

Year: Lake Powell fill obligations to achieve equalization with Lake Mead storage

Seasonal: peak heating and cooling months

Daily monthly: Flood control operations, Kanab ambersnail impacts

Hourly: Western Area Power Administration's power generation decisions

SPATIAL SCALES

Global: Grand Canyon National Park World Heritage Site, large-scale climatic influences

National: Western water development: irrigation, Grand Canyon Protection Act (1992)

Regional: Prior appropriation, Upper Colorado River Commission, Upper and Lower Basin agreements, energy grid, differential hydro-climatic impacts

State: Different agreements on water marketing within and out-of-state, Water Districts

Municipal: community-household

The hydro-climatic decision calendar: adaptive management and the annual operating plan

As noted by the National Research Council's Committee on Grand Canyon Monitoring and Research (National Research Council, 1999a):

'The Glen Canyon Adaptive Management Program aims to monitor and analyze the effects of dam operations on downstream resources in the Grand Canyon ecosystem and to use that knowledge to recommend on a continuous basis, to the US Secretary of the Interior, adjustments intended to preserve and enhance downstream physical, cultural and environmental values'.

The concept of Adaptive Management (AM) as applied by GCDAMP is based on the recognized need for operational flexibility to respond to (1) future monitoring and research findings and (2) varying environmental and resource conditions over the long term. The key principles for operationalizing AM are: (1) cooperative management (shared decision-making authority), (2) allowances for local variations in management strategies, and (3) systematic learning using experimental designs. The benefits and limitations of this approach have been summarized in Walters (1998). Primarily, problems surrounding the implementation of adaptive management programs have been associated with (1) the maintenance of long-term monitoring and observations efforts, (2) constraints on the ability of public sector managers to make risky but potentially beneficial decisions, and (3) conflicts between traditional needs, such as hydropower, and newer values, such as ecosystem restoration (Lee, 1993; Pulwarty *et al*., 1995). The present study is not intended to be a critique of the GCDAMP, of AM as a concept, or of present understanding of how long-term physical and biological dynamics within the Grand Canyon are affected by dam operations. Full descriptions of the GCDAMP approach can be found in Webb *et al*. (1999) and National Research Council (1999a). Instead, the paper is meant to illustrate the importance of the decision-making structure, such as that developed by the GCDAMP in promoting flexible management strategies in the face of environmental uncertainties, such as climate variations and changes, and in consideration of potentially conflicting management goals.

Experiments tied to the operation of GCD form the basis of the AM Program. Effective adaptive management in the Grand Canyon region requires trade-offs among the management objectives favored by different groups. Controlled high flows – termed Beach/Habitat-Building Flows (BHBFs) – are the primary management tools employed by the GCDAMP for Grand Canyon ecology and habitat maintenance. BHBFs and other restoration operations result in the transfer of benefits from water and hydropower interests to those representing ecological and recreation concerns. Much of the discussion at TWG and AMWG meetings focused on the tradeoffs between the requirements of AOP (Spill Avoidance Discussions, 1998) and on carrying out BHBFs. The following is a brief discussion of the AOP and BHBF requirements in the context of GCD management decisions and climate variations within the region.

The annual operating plan

GCD holds 79% of total storage in the Upper Basin and generates 78% of the total hydropower production. As a result of climatological droughts experienced during the 1930s, 1950s and in 1977 (at 7·2 $\mathrm{Gm^3yr^{-1}}$ the second driest year on record) the Colorado River Storage System is operated through the Annual Operating Plan (AOP) to maximize the amount of water in storage for protection against dry years. The AOP was developed in accordance with the Colorado River Basin Project Act (1968) criteria for long-range operation of Colorado River reservoirs and is administered through the Colorado River Management Work Group, consistent with the Law of the River. One of the key requirements of the system-wide AOP is that the volumes in Lake Powell behind the GCD and downstream in Lake Mead behind Hoover Dam be equalized at the end of the water year (October–September). Lake Powell and Lake Mead (each with over 30 $\mathrm{Gm^3}$ storage capacity) are the largest human-made lakes in the United States. The Grand Canyon occupies most of the area between them (Figure 1).

GCD management and all other major dams within the Upper Basin use information derived from a 24-month model of the Colorado River Storage System. The operating rules are not linear decision rules but more of a heuristic for consideration of optimistic and pessimistic runoff scenarios from available snowpack (i.e. reactive to current conditions) and observing the range of possible storage conditions that may result (Hughes, 1991).

A simplified description of the AOP criteria is as follows:

(1) Annual release at Lee Ferry: only $10{\cdot}2\,\mathrm{Gm}^3\mathrm{yr}^{-1}$ average minimum is released (i.e. the compact requirement) unless there is a significant probability of spills during the *next* runoff season.

(2) Monthly target releases: in each year the monthly targets are allocated to create a flood storage space behind GCD (Lake Powell) of about $3\,\mathrm{Gm}^3$ on January 1 and to be within $0{\cdot}6\,\mathrm{Gm}^3$ of full by July 1.

For water year (WY) 1998 the primary purposes of the Annual Operating Plan (AOP, 1998) were to determine: (1) the projected operation of the Colorado River reservoirs to satisfy storage and use requirements under varying hydrologic and climatic conditions; (2) the quantity of water considered necessary as of 30 September 1997 to be in storage in the Upper Basin reservoirs as required by the Colorado River Basin Project Act; (3) the quantity of water available for delivery pursuant to the 1944 Mexican Water Treaty and the International Boundary and Water Commission between the United States and Mexico; and (4) whether the reasonable use requirements of mainstream users in the Lower Division States will be met under a 'normal', 'surplus', or 'shortage' condition as outlined in Article III of the Operating Criteria.

Interestingly, the Law of the River controls the yearly operation of the dam, especially in cases of extreme shortage, but does not control the daily operations for power generation. The US Bureau of Reclamation is responsible for the monthly and annual release targets at GCD while the Western Area Power Administration (WAPA) operates the daily flows subject to the above monthly target release. Monthly release targets are aimed at achieving the AOP criteria, while hourly schedules to meet the monthly target are heavily influenced by power demands and minimum flow requirements. Prior to 1983 the operating target was a full reservoir. Since that year a compromise among the operations management groups has led to the establishment of the monthly targets described above. This action, combined with a redistribution of monthly release patterns agreed to under the AOP, was meant to effectively reduce the estimated frequency of unanticipated flood flows, similar to the 1983 peak (discussed below), to less than 1% each year. Thus a second major goal of the AOP in any year is to avoid spills at the GCD.

Beach habitat building flows (BHBFs)

A BHBF is defined to be a flow in excess of GCD powerplant capacity by at least 30% but not more than 35%. BHBFs are intended to be implemented to the extent necessary to: (1) protect river sediment storage downstream, and (2) reshape river-channel topography and redeposit sediment on sandbars to enhance aquatic and terrestrial habitats. Using this relatively low-cost tool (Welsh *et al.*, 1999) requires increased attention to storage and release decisions that are made in response to changing hydrologic conditions in the Basin. Hereafter BHBFs will refer to experimental releases specifically oriented towards sediment redistribution for environmental and habitat needs, in order to distinguish them from other releases for power generation, dam safety etc.

The highly-publicized spring 1996 BHBF-Test flow was implemented following discussions between the Department of the Interior, the Basin States, other involved stakeholders, and scientists (Webb *et al.*, 1999). This controlled flood occurred as a seven-day release of 1274 cubic meters per second. It was the result of a decade-long evolution in scientific thinking about the appropriate role of high flows in the management of the Colorado River in Grand Canyon (Schmidt *et al.*, 1999) and was implemented under the Glen Canyon Environmental Studies program, the forerunner of the GCMRC (see Wegner *et al.*, 1995; Webb *et al.*, 1999). Final implementation of the 1996 BHBF necessitated revision of the estimates of appropriate system-wide runoff conditions that would be needed to trigger such releases. These releases would have to occur in a manner consistent with the 1956 Colorado River Storage Project Act, the 1968 Colorado River Basin Project Act, and the 1992 Grand Canyon Protection Act.

BHBFs were first proposed as part of the Environmental Impact Statement recommendations (DOI, 1995). The Colorado Basin states initially objected to BHBFs on legal grounds as violations of the 1968 Colorado River Basin Project Act, which limits spills (see AOP discussion above). An agreement was reached where experimental flows would be carried out when releases in excess of powerplant capacity were likely to be required for dam safety (i.e. high inflows coupled with a relatively full reservoir) in accordance with the triggering criteria discussed below (Schmidt *et al.*, 1999).

The Biological Opinion (DOI, 1995), requires that conditions suitable for endangered and other native fish species be provided by evaluating and simulating hydrologic patterns similar to the pre-dam hydrograph (Figure 3). Alternatives are evaluated for high spring flows, stable summer flows, water temperature modification, and sediment

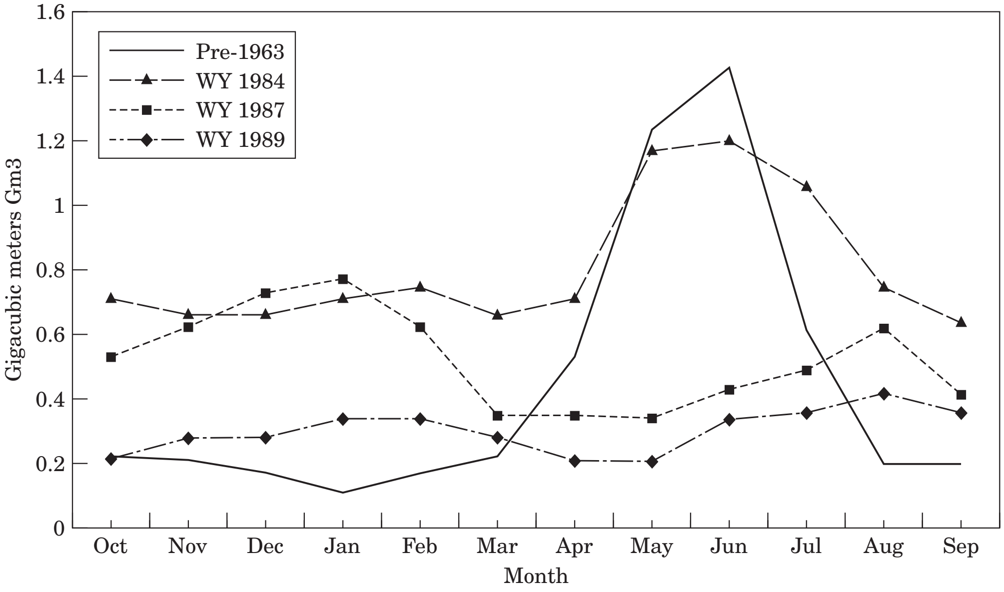

Figure 3. Mean monthly pre-Glen Canyon Dam streamflow and subsequent releases for selected years at Lee Ferry: Pre-1963 conditions (prior to GCD) and power-plant releases during WY 1984 (very high runoff), WY 1987 (moderate runoff), and WY 1989 (low runoff).

augmentation. During WY 1998, hydrologic triggering criteria for BHBF's were developed by the TWG. These criteria govern when such flood flows may be implemented and when deemed appropriate from an environmental perspective by the AMWG. A trigger is met:

(1) If the forecast made on January 1 for the following April–July unregulated runoff into Lake Powell exceeds 16·2 Gm^3 (about 140% of normal) when the January 1 storage is 26·7 $\text{Gm}^3\text{yr}^{-1}$ (i.e. when the sum of forecasted runoff and reservoir storage exceeds 42·8 Gm^3 on January 1), or

(2) If any later monthly forecast for spring runoff into Lake Powell would require a powerplant monthly release greater than 1·9 $\text{Gm}^3\text{yr}^{-1}$.

The triggers rely on information about present conditions and forecasted runoff. The triggering criteria were determined such that the magnitude of risks associated with BHBFs was agreeable to all stakeholders on the AMWG, and are designed to preserve the agreement which allowed the 1996 BHBF test to occur (current ROD). Once a runoff trigger is met, the decision to release a BHBF is made contingent upon Upper Basin hydrologic conditions and additional resource and costs criteria, including several endangered species recovery plans. Either of the above triggers requires estimates of flows a month to a season in advance.

Under the current BHBF agreement and the Biological Opinion, experimental floods are limited to the winter-spring period and are prohibited during the high-energy demand months of the July–September 'monsoon' period. The ROD stipulates that BHBFs will be implemented only in years when there is the likelihood for flood-flows to be released from the dam for emergency purposes. Control of GCD discharge before and following a BHBF is most problematic when the reservoir is high because of dam safety concerns governing water releases. However, without altered storage release strategies (described below), the hydrologic triggering criteria effectively confines likely BHBFs to the May–June period in high inflow years.

In the first week of November 1997 a second BHBF was released to redistribute sediment resources within the Grand Canyon and in order to prevent material loss to Lake Mead downstream. This release was sanctioned after severe storm events in the late fall resulted in over a million tonnes of sediment being washed into the Colorado from the Paria River above the Grand Canyon. It was also an experiment to test the impacts of short duration flows on Grand Canyon sediment resources and ecology. The plan encountered little opposition from water and power interests, especially since no water was allowed to bypass the powerplant.[1]

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[1] 1 million acre-feet (the unit of volume used operationally by the US Bureau of Reclamation) approximately equals 1·24 gigacubic meters (i.e. 1·24 billion cubic meters).

The hydro-climatic decision calendar

Changing risks from climate variations within each runoff season, together with growing operational constraints from economic, legal, and environmental requirements complicate efforts to produce a single simple BHBF trigger or to follow the AOP precisely. A major activity for the TWG/AMWG is information gathering and evaluation of scenarios for experimental flow releases from GCD, such as in 1996. During 1997 and 1998 the TWG met monthly, and reported to the AMWG which met on quarterly basis to evaluate likely scenarios of runoff, among other issues. This process occurred in parallel with that of the AOP, and converged at the BOR operational decision-making points during the forecast-runoff period. Based on interviews and GCMRC reports, a 'hydro-climatic calendar' of information gathering and decision-making is outlined in Figure 4 (also D. Garrett, pers. comm.). This calendar was employed by the authors to identify entry points for appropriate climate-related information in the Annual Operating Plan for Upper Basin and in the AMWG process for BHBFs. Since the AMWG was only fully initiated in late-1996 the 1997–1998 period was also the first test of the coordination of these two processes. The decision calendar is based on similar scheduling tools used in agroclimate and other studies, where timing of activities are contingent on seasonal transitions and their impact on physical or biological systems. Its effective development and use requires an understanding of the nature of these climatological transitions and changes, and relevance to management activities.

Climatology, variability and forecasts

Water managers throughout the system have traditionally relied upon the historical record in order to plan for the future, inferring the probability that shortages and floods might occur given their frequency of occurrence in the past. Seasonal forecasts of snow pack and streamflow play significant roles in meeting management needs for the AOP (interview notes). The two factors most often used for spring streamflow forecasts prior to the spring runoff period are: (1) April 1 snowpack conditions, i.e. accumulated over the winter-season months (December through March), including snow-water-equivalent, and, (2)

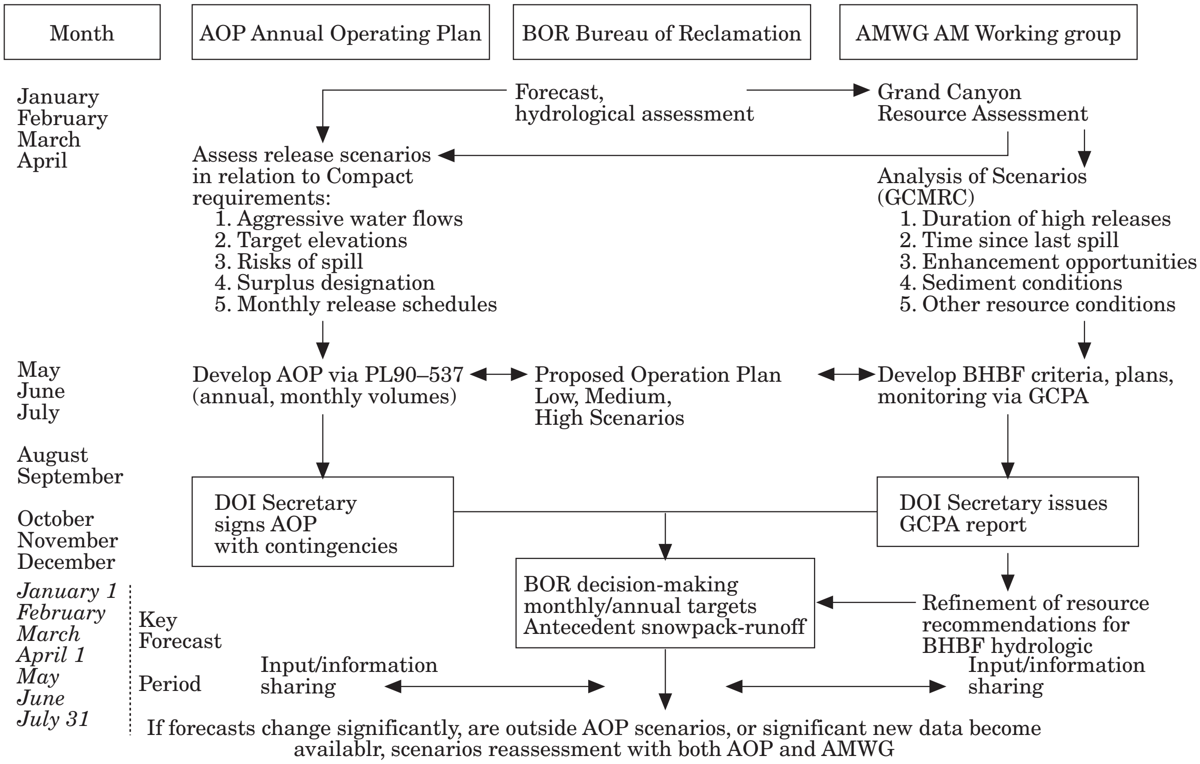

Figure 4. Adaptive Management Program calendar of information gathering and hydro-climatic decisions at Glen Canyon Dam.

antecedent conditions as indicators of soil moisture (water retention capacity).

A 'spill' occurs when power plant capacity is exceeded, usually for flood control or dam safety purposes. Spill risk is thus high if the reservoir is filled during the preceding year. The lowest point of storage in Lake Powell during the water year usually occurs in March as a result of January through March releases at GCD (Figure 4). Preemptive releases are required to avoid flood flows when storage in Lake Powell is already high. Errors in streamflow forecasts are usually expected to decrease as the snow accumulation progress into the runoff seasons. However, large forecast errors associated with snowmelt-runoff transformations in late-spring and early-summer have occurred in the past (Figure 5). The authors and colleagues have shown that the correlation between streamflow at Lee Ferry and precipitation in the Upper Basin to be only about 0·6 ($P<0{\cdot}01$) (Melis *et al.*, 1999). The streamflow forecasts (and their accuracy) driving late-winter and spring operations at Glen Canyon Dam thus significantly impact the capacity for accommodating unanticipated late-season inflows.

Studies have indicated that the warm tropical Pacific phase of ENSO during Northern Hemisphere winter is associated with diminished snowpack and stream-flow in the Northwestern United States, and enhanced snow pack and stream-flow in the Southwestern US (e.g. Cayan, 1996; Cayan and Webb, 1992). The ENSO signal within the Colorado River Basin is complex between upper and lower contributing areas, and is not as consistent as in other parts of the world (e.g. Australia, California and Peru, see Glantz, 1998). Mean changes in snow-water-equivalence during warm ENSO years depict a transition between drier than average conditions in the north and wetter than average condition in the southwest (Clark, 1999). Climatic impacts during cold ENSO events (La Niña) are usually of opposite signs to that during warm events. For January through March, precipitation on the Colorado mainstem above the confluence with the Green River is reduced to about 88% of normal during warm ENSO events (see Figure 1). In the San Juan basin winter precipitation usually increases to 140% of normal, while in the source region of the Green River in Wyoming precipitation is usually reduced to 70% of normal (CPC, 1999).

Most studies have focused on ENSO relationships with the snowpack accumulation period prior to April 1. There is increasing evidence that particular ENSO-events influence the seasonal variability of snow-pack and high-elevation temperatures that might promote the likelihood of extreme runoff events throughout the Upper Colorado River Basin. It is not yet clear whether this is owed to modulations of timing controls or magnitude or both for different events. As shown in this study, particular

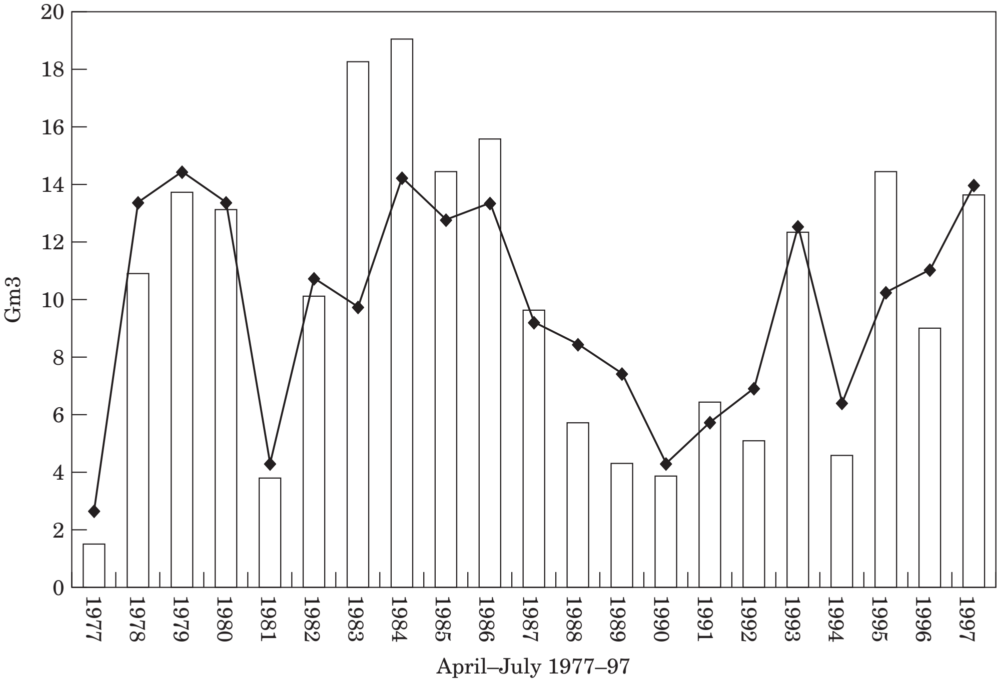

Figure 5. Lake Powell observed inflow (□) and April 1 forecast (▲) for April–July totals 1977–1997.

ENSO events may be associated with significant runoff in the spring-summer transition after this date, while the internal atmospheric dynamics in other years may lead to minimal impacts. This presents a significant management problem in many areas where the overall association of ENSO with extreme climatic events may be small based on correlations but may be catastrophic for a smaller number of particularly extreme events. For WY 1998 this problem was complicated by the fact that the 1997–1998 and 1982–1983 events were the two outliers (i.e. most extreme in the 20th century), and in addition, evolved differently over their lifecycles. This is discussed further below.

Two other important features driving southwestern US climate are the summer monsoon and tropical perturbations migrating north from the central Pacific in late summer. The onset of the southwest monsoon marks a pronounced transition from a dry June to a rainy period from July through mid-September (see Adams and Comrie, 1998). This wet regime extends from northern Mexico through southern Colorado. While the monsoon and tropical depressions are not major contributors to mainstem stream flow at Lee Ferry, they do drive high sediment deliveries from the Colorado tributaries in and above the Grand Canyon. The relationships between these features and ENSO events are not well understood.

Until recently, awareness of these climatic influences has been limited (Webb *et al*., 1995). Even after the events of 1983, the GCD Final EIS (DOI, 1995), now the baseline for AM modeling efforts in the Colorado River Basin, was carried out over the same period as the 1991–1994 ENSO event. No stakeholder when interviewed recalled explicit consideration of this extended ENSO event as possibly creating an anomalous background against which these baseline studies were being carried out. In fact, at the start of this study one interviewee (a researcher) responded that 'the Dam has effectively removed climate variability from the Grand Canyon'.

Beginning in mid-1997, immense media and public attention across the US focused on the very strong ENSO warm conditions developing in the equatorial region of the Pacific Ocean. At the national level, the memory of the impacts of 1982–1983 (which were beginning to occur in other parts of the world) and forecasts of further such impacts promoted the demand by national agency directorates for their regional offices 'to do something about ENSO'. These demands involved pressures on many of the GCD stakeholder groups. As noted by Brunner and Klein (1999) public calls to 'do something' are rarely if ever accompanied by clear definitions of the issues or variables being forecast or of recommendations for action. At the start of the event, concerns raised among the GCDAMP stakeholder groups included questions such as:

(1) What is the impact of ENSO on the region?
(2) Will this year be similar to 1983?
(3) How would this particular event affect the forecast for streamflow timing and magnitude?
(4) What are the uncertainties and what (if anything) should be done in light of them?
(5) How can (practical) action take place given the constraints on the system?

As discussed below, careful analyses of experiences during past extreme events together with a decision environment conducive to the application (and questioning) of new information provided important conditions for guiding actions during this potentially 'surprising' situation.

Focusing events: recent climatic extremes

Focusing events are associated with exceptional societal visibility and/or environmental impacts (Birkland, 1998). They usually expose critically vulnerable conditions and test management assumptions. Two such events occurred at GCD in the late spring and early summers of 1983 and 1995. In addition to these types of events there are also those climatological extremes that are successfully managed and from which confidence in the present system is reinforced. One event of this type occurred at GCD in 1984. The impacts of these events are now discussed leading up to a description of management actions taken during WY 1997–1998, when the GCDAMP had been established.

The two wettest years in the Upper Basin during the last century were 1983 and 1984. These had 29·8 and 30·4 $\mathrm{Gm^3 yr^{-1}}$ accumulated inflow to Lake Powell, respectively. Both events occurred under full antecedent reservoir storage conditions. These two extreme runoff years were, however, completely different with respect to runoff timing and were therefore anticipated and responded to very differently by river managers. It was clear by early January 1984, based on accumulated snowpack, that the runoff season would be much higher than average (Table 3 and Figure 5). Thus, even though that year was extreme in a climatological sense, it was not a significant management problem. In contrast, the 1983 monthly forecasts from January through April of that year indicated that average or below normal (April through July) runoff would occur. Dam operators were led into following what turned out to be a very erroneous forecast (and error magnitude) under full storage conditions. By the end of the April–July 1983 period, the accumulated runoff had increased to 240% of the average April–July inflow since the completion of GCD (1965–1982). The spillways on the Dam were overwhelmed and cavitation began to occur within its tubes (Falvey, 1990). There was little time for flood mitigation actions once it was clear that the bypass structures on the Dam had failed (Rhodes *et al*., 1984).

In addition to extreme late-spring precipitation, the most important factor modulating this runoff was the shift from warmer to colder than normal temperatures at high elevations. The temperature regime shifted after April 1 and persisted through July, keeping significant snowpack on the higher elevations into summer (see Table 3). The importance of changes in post-April 1 conditions was first elucidated by the authors, and presented to the AMWG and to reservoir managers. Previously, attention in the research literature had focused for the most part on the accumulation period up to April 1. Whether or not the extreme total runoff in 1983 was owed solely to conditions created by the 1982–1983 ENSO event is still unclear. The memory of widespread uncontrolled flooding and the real possibility of complete dam failure at Glen Canyon in 1983 (Upper Colorado River Basin Commission, pers. comm.) still reverberates among managers in the region, even among those who were not in management positions at that time.

Table 3. Forecasts of April–July runoff since the closure of Glen Canyon Dam, and average upper level seasonal temperature anomalies. Flow conditions in years shown would have met the 1998 hydrological triggering criteria for BHBFs (Melis *et al*., 1999) Years in bold font are discussed in detail in the text. Late winter = Jan–Mar; spring = Apr–June

Year	April–July mean inflow to Lake Powell Gm^3			Upper Basin high elevation temperature anomalies °C	
	January 1 forecast	April 1 forecast	Observed totals	Late-Winter	Spring
1965	11·9	14·1	14·0	−1·5	0·5
1973	12·5	11·2	14·0	−1·0	−2·0
1983	9·7	9·8	18·4	0·8	−2·0
1984	16·1	14·3	19·1	−1·8	−1·5
1985	14·3	12·8	14·5	−1·8	0·5
1986	13·1	13·4	15·6	1·5	0·5
1995	7·4	10·3	14·5	1·5	−2·0
1996	7·8	11·0	9·1	1·0	1·0
1997	14·9	14·9	14·1	1·5	−0·5
1998	8·2	8·4	9·5	0·8	−0·8

A similar inflow situation occurred again in late spring 1995 (April–July 14·5 Gm^3), when the error of the January forecast was greater than 7·0 Gm^3 (in a 19 Gm^{3}yr^{-1} system). This was, incidentally, after the longest recorded period of warm ENSO conditions in the Pacific beginning in 1991 and lasting through 1994. Inflow into Lake Powell was over 150% of normal for April through July. Precipitation levels in May and June were over 200% of average throughout the Upper Colorado Basin, while cooler than normal temperatures delayed the onset of runoff. The initial under-forecasting of the high runoff in 1995 (25·8 Gm^3 total) did not raise concern among the public, but did so among the GCD reservoir managers. Fortunately, the low reservoir conditions resulting from several previous dry years between 1987–1994 (Figure 2) allowed for the 1995 inflow to merely increase system-wide storage with little public visibility of risk. Had Lake Powell storage been high in 1995, flood magnitude releases would have had to be made in a short time. There was little awareness in 1995, as in 1983, of the switch in high elevation temperatures in late spring (Table 3). Another significant aspect of the 1995 runoff event was that it allowed Lake Powell to achieve full capacity again after nearly a decade, setting up high antecedent reservoir storage conditions for WY 1996–1998. By the end of 1997 there was little memory of the unanticipated late and high magnitude 1995 runoff, except among a few operations personnel (interview notes) – i.e. it was a management but not a public focusing event.

Operations in Water Year 1998: the ENSO event

Total unregulated inflow to Lake Powell during WY 1998 was about 116% of normal (DOI, 1999). At the beginning of the runoff season the basin wide snowpack was 100% of normal but soil-moisture conditions and winter runoff were above normal owing to anomalous wet conditions throughout 1997. During the winter of 1997 (October–December) scheduled releases from Glen Canyon Dam remained above those suggested by the replacement inflow. These releases continued through January–March 1998 in spite of low runoff forecasts (Figure 6). With

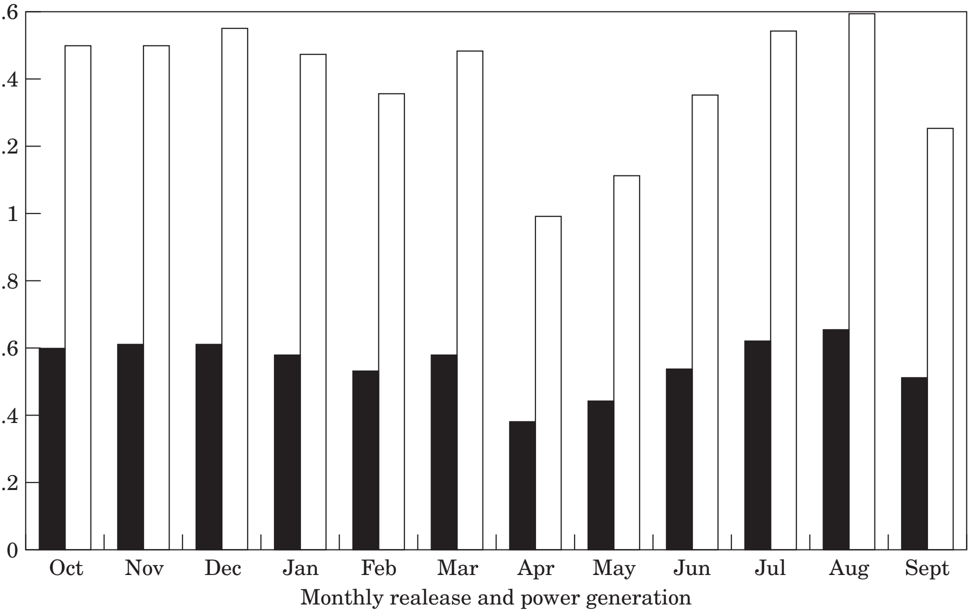

Figure 6. Glen Canyon Dam monthly powerplant releases (billion cubic meters, ☐) and generation (billion kilowatt hours, ■) during WY 1998.

the Upper Basin storage reservoirs nearly full, and the potential threat of El Niño-related precipitation extremes in the Lower Basin, minor releases were also made from Hoover Dam on Lake Mead. In total, 1·4 Gm^3 were released above downstream requirements during these three months. In the last week of March 1998, an unexpected northward displacement of the jet stream reduced the chances for a repeat of 1983 conditions. However, the displacement resulted in high Green River flows, at about 130% of normal, later that spring. Wet and cold conditions maintained much of the Green River basin snowpack in June and delayed melting. This water was however easily accommodated by the space created from earlier releases and by additional powerplant releases (to about 560 cm/sec) between July and August (Figure 6).

As mentioned above, as of fall 1997, few forecasters and managers had paid attention to the potential for dramatic seasonal shifts in snowpack accumulation in late spring 1998 or to the likelihood for high-elevation cold temperature anomalies (interview notes). All of this could have been learned from the 1983 and 1995 high runoff events. Thus the additional reservoir drawdown of Lake Powell in spring 1998 was an exceptional move. Through the process described above, climatic information relevant to the timing of particular decisions for winter 1997 and spring 1998 was made available by the authors and discussed with AMWG and TWG representatives. River managers acted on historical data on both precipitation and temperature, particularly with respect to 1983 and 1995 and the actual evolution of regional climate related to the ENSO event, i.e. instead of operating solely on the basis of the early, below average runoff forecasts. Their action constituted a unique and conservative management strategy to prepare for potentially higher than forecast spring runoff on the basis of prior experience, and new information provided by the authors on past events and the evolution of present conditions (see Table 3 and above Section).

The April through July unregulated inflow into Lake Powell in WY 1998 was 9·5 Gm^3 (112% normal), 1·2 Gm^3 greater than the January 1 streamflow forecast (Table 3). More importantly, it was delayed, as in 1983 and 1995, until well past the historic peaking period and with rapid descent. While WY 1998 did not have the extremely high spring precipitation, or as large a shift in magnitude from warm winter to cold spring upper-level temperatures that characterized WY 1983, it posed a forecast and management problem in a different way. In spite of high releases made since October, the decision to make continued high releases through early spring had to be made by late December 1997, a time when most projections are likely to assume normal subsequent conditions based on historical mean data. In addition, considerations for BHBFs, non-existent in 1983 and 1995, had to be made (see following section). At the end of the 1998 melt season, Lake Powell was filled to within 0·6 Gm^3 of total capacity, precisely as required by the AOP. While this final fill situation did not allow a BHBF to occur during spring it also did not restrict the likelihood of a BHBF for later that year. In the end, all GCDAMP stakeholders expressed satisfaction with final outcome (Post-event notes).

Tradeoffs: all extremes will not remain equal

In 1998, river managers faced considerable pressure from both power and environmental groups to limit higher than normal (forecasted) flow releases during winter and early spring 1998. Hydropower interests were concerned that a dry late spring and summer might follow the release, further diminishing the water available for powerplant operations. The additional drawdown was more than 1·2 Gm^3 above the storage that would have otherwise been available at the end of the spring runoff season. Environmental groups felt that if releases continued through spring, then the triggering criteria would be eliminated apriori for a late-1998 BHBF. In addition, it was thought that high constant flows throughout spring would degrade downstream sediment supply in the main channel. Most importantly, the early spring releases were viewed by non-hydropower groups as possibly setting a precedent for power interests to use future requests for dam safety and flood control releases as opportunities to limit the chances of BHBF triggers for environmental flows to be met.

It was clear at the close of WY 1998 that if releases had not been made from GCD during early spring, a spill event of 0·6 Gm^3 would have occurred at the beginning of summer (BOR operations interview notes). In addition, even if a runoff event of similar magnitude and timing to 1983 had occurred, crisis situations and damages would have been lower by comparison. The factors that influenced and facilitated actions during this time are summarized in Table 4. The GCDAMP provided a forum and participatory setting in which representatives of stakeholder groups in the Grand and Glen Canyon regions could view and evaluate the changes in operational action and regional climate as the ENSO event evolved.

As opposed to a deterministic prediction in which all the variables and their interactions are known,

Table 4. Factors in the decision to prepare for the 1997–1998 ENSO event and to use climate information in Water Year 1998 at Glen Canyon Dam

1. Past events of importance:
   (a) 1983 as a focusing event for public and private concerns: Association of high runoff with 1982–1983 ENSO
   (b) 1984 as a high but anticipated runoff event with successful mitigation
   (c) 1995 as a focusing event for GCD managers: 7 Gm^3 forecast error
   (d) 1997 antecedent high runoff conditions (140% of average inflow to Lake Powell)

Consequences of flood events seen as more direct than drought: Reservoir has 2–4 year buffer capacity for dry periods

2. ENSO 1997–1998
   (a) Regional/National pressures to 'do something about El Niño'
   (b) Concern about an exceptional event or surprise

3. Acceptability of climate information. Enabled by:
   (a) Trust in reservoir manager by upper basin interests based on long-term involvement
   (b) Increased credibility of climate information providers through interaction and participation over the water year and explicitly addressing concerns/doubts about past events, forecasts etc.
   (c) Present study viewed as joint effort between along-standing participant within the GCDAMP setting (T. Melis) and climate researcher (R. Pulwarty)

5. Usability of climate information. Enabled by:
   (a) Willingness of climate researchers to develop an appreciation of the context and procedures for decisions within the basin (e.g. AOP vs. BHBF tradeoffs, role of RFC vis-a-vis BOR, power, flood control, environmental needs etc.)
   (b) Explicitly addressing known barriers to information use obtained from previous studies
   (c) Communicating key components of climate variability in region through data presentation to stakeholders
   (d) Exercises in climate data analysis with reservoir manager, i.e. validation of knowledge claims made by climate researchers
   (e) Identifying thresholds (that matter) passed in year to date (also other regions)

6. Judgement and experience of reservoir manager: realizing when more information would not help and making the decision to allow increased releases

7. Flexibility and facilitation of interaction allowed through the information gathering, planning and decision environments provided by the Glen Canyon Dam Adaptive Management Program

forecasts are probabilistic in nature implying a spread of outcomes (Pulwarty and Redmond, 1997). Instead of making a single discrete decision at the start of the season, the response at GCD during 1997–1998 was a process of planning for likely scenarios based on past experience and, of hedging actions in accordance with the AOP/BHBF procedures as new information arose. Despite below normal forecasts in early 1998, BOR allowed higher than expected releases from Glen Canyon Dam. The justifications for this change were the higher than normal fall 1997 streamflow in the upper basin and the potential for a repeat of the 1983 and 1995 runoff conditions (i.e. full reservoir antecedent conditions, low early spring forecasts, then late high-magnitude runoff).

Interestingly, it may now be believed that all such events can be managed with present operations and that there is no need to be concerned with ENSO. The risk is that the lessons of 1983, 1984 and 1995 and the measures employed during 1998 may now be discounted by the larger public. In fact, one interviewee noted that in early spring members of the group he represented began to refer to the 1997–1998 El Niño event as 'El No-show'. Greater awareness of climatic issues does seem to have been incorporated within the GCDAMP process. The GCMRC and the TWG now explicitly include climate information of the types discussed in this study, in presentations to the AMWG, and in the adaptive management conceptual model. In addition, efforts have begun at the National Weather Service River Forecast Center in Salt Lake City, to move away from the reliance on historical means alone and towards statistically conditioning runoff projections on climate forecasts during ENSO years (NWSRFC, 1998). Coordination of activities at the BOR and the NWSRFC must continue to be improved if ENSO forecasts are to have increased value to dam managers through this formal mechanism.

Conclusion and recommendations

In the Colorado River Basin, requirements to balance economic interests, environmental management objectives and the Law of the River are directly dependent on changes in available water and, controls on its variability including climate. Interviews reveal however that water resource managers believe that much of the research-based climate information they receive is not readily understandable and/or is not sensitive to the unique situations in which they must act. While there has been increasing focus on the processes by which scientific knowledge has been produced and more recently communicated to user communities, less time has been spent examining the capacity of audiences to critically assess externally provided information (e.g. climate forecasts) within their own decision environments (Fischoff, 1996). In this study, the ability of practitioners to question and manipulate the data, and to reconcile scientific claims with their experience and schedules, played important roles in their choices and the acceptability of those choices in the broader setting (Table 4).

The National Research Council (1999a) has since recommended that the GCDAMP consider, among other sources, using hydropower revenues at the levels currently provided to support core research, monitoring, and adaptive management programs. For these purposes the present study shows that, in addition to April 1 snowpack accumulation, there is a need for tracking climate-related parameters that govern monthly and bi-weekly forecasts issued *during* the main spring runoff period (April through July). Information is needed within both the AOP and AMWG processes on (1) the variability and extremes of precipitation after the end of the normal accumulation season (April 1), and (2) the historical timing of spring snowmelt and its magnitude and duration including snowpack-runoff relationships. Careful application of such climatic information can result in enhanced storage readiness for hydropower production during summer. BHBFs could thus be timed to follow the summer and fall sediment input season improving the likelihood that inputs are conserved upstream (see Hazel *et al.*, 2000). As configured at present, the triggering criteria alone do not give scientists sufficient time to deploy equipment and personnel to monitor effects of the high flow (Walters *et al.*, 2000).

By themselves, extreme events and corresponding scientific information do not necessarily result in appropriate lessons being applied or even learned. Effective use of probabilistic climate information, especially in increasingly multi-objective and value-laden settings, requires flexible information-gathering decision and evaluation environments such as provided by the GCDAMP. Such groups should have explicit responsibilities for considering the consequences of particular decisions across the relevant time and space scales to avoid undermining long-term goals, such as ecosystem management, with shorter term adjustments such as for flood control (see Table 2). The GCDAMP meetings and structure (e.g. TWG consensus on information presented and then ratification within the AMWG) offered the opportunity to explicitly address these concerns in an open setting, without restricting information to one group (usually presumed to be technically sophisticated) over another.

Based on this study, we conclude with the following recommendations for researchers and practitioners cooperatively engaging in the use of climate information, including forecasts:

(1) Describe the hydro-climatic calendar/annual cycle of decisions of different processes (planning, information gathering, forecasting, decisionmaking, implementation evaluation, etc.) to identify entry points for relevant climatic information and competing pressures at different stages (see Figure 4)
(2) Clearly document single historical events of significance and evaluate the contexts within which decision-making occurred, including lessons learned and incorporated. Adjustments and lessons accumulated over time (e.g. during and after 1983, 1984 and 1995) provide insights into actions recommended by managers, forecasters and researchers in responding to current events. Key emphasis should be on analyses of the role of these antecedent decisions on constraining or enabling alternatives recommended during rapidly developing events
(3) Evaluate decisions within the context of longer-term climate variations such as decadal-scale wetter and drier periods. This includes evaluating the cumulative impacts of shorter multi-year variations (e.g. 1987–1992 dry period) and antecedent physical conditions (e.g. 1995–1997 high runoff)
(4) Clarify fundamental features and gaps in knowledge of climate-runoff relationships relevant to the problem at hand. For the Colorado at GCD, the importance of controls on post-April 1 runoff in different sub-basins and the controls and influence of late-summer monsoon conditions on sediment flow into the Grand Canyon are not well understood. These factors may also play extremely important roles in timing experimental high flow releases should extended dry periods occur.
(5) Treat the development, communication, and use of climate (and other scientific) information as a process where symmetrical learning takes place between providers of scientific information and practitioners over time. Researchers, through ongoing dialog and joint studies, should engage practitioners as full partners in uncovering issues of mutual significance, explicitly address uncertainties, and known barriers to information use (see Pulwarty and Redmond, 1997), uncovering those contingent on each situation. The goals are to have better matches among what is needed, what is asked for, what is provided and, what actions can be taken. These processes must be embedded within an understanding of the decision contexts within which trade-offs take place (such as between the AOP and BHBF criteria)

Climatic change projections for the Colorado indicate the likelihood of alterations in seasonal runoff timing and shape (Gleick and Chalecki, 1999). Given projected social and environmental changes (including decadal-scale shifts in event occurrence) extreme-event research and applications may be expected to assume greater immediacy (Changnon, 1995), with particular emphases on the public sector e.g. operation for traditional uses as well as for meeting environmental and cultural requirements. Cognizant of the above recommendations, such studies can also identify field-tested alternatives for actions in other regions, especially in settings where the decision stakes are complex and the system uncertainty is large.

Acknowledgements

We wish to thank David Garrett (GCMRC) and Randall Peterson (BOR) without whose help this study could not have been completed. The comments of the Editor and three anonymous reviewers significantly improved the paper. This study was funded in part by the NOAA Office of Global Programs and NSF EAR 9634329.

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Appendix: List of acronyms

AM	Adaptive Management
AMWG	Adaptive Management Working Group
AOP	Annual Operating Plan
BHBF	Beach Habitat Building Flow
BOR	Bureau of Reclamation
DOI	Department of the Interior
ENSO	El Niño–Southern Oscillation
GCD	Glen Canyon Dam
GCDAMP	Glen Canyon Adaptive Management Program
GCMRC	Grand Canyon Monitoring and Research Center
GCPA	Grand Canyon Protection Act
NOAA	National Oceanic and Atmospheric Administration
ROD	Record of Decision
TWG	Technical Working Group
WAPA	Western Area Power Administration
WY	Water Year (October of previous through September of present calendar year)