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The state of the Colorado River ecosystem in Grand Canyon: Lessons from 10 years of adaptive ecosystem management

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ABSTRACT
The year 2005 marked the 10th anniversary of the completion of the Final Environmental Impact Statement (EIS) on the Operation of Glen Canyon Dam on the Colorado River, USA. A decade of research and monitoring provides an important milestone to evaluate the effects of dam operations on resources of concern and determine whether or not the desired outcomes are being achieved, or if they are even compatible with one another or not. A comprehensive effort was undertaken to assess the scientific state of knowledge of resources of concern, as identified in the EIS. The result was the first systematic attempt by scientists to conduct an assessment of the changing state of Colorado River ecosystem resources in Grand Canyon over a decadal timeframe. In the EIS, 30 resource attributes are listed along with predictions for how those resources would respond under the Secretary of the Interior's 1996 Record of Decision, an operating prescription based on the preferred alternative of Modified Low-Fluctuating Flows (MLFF). Because of a lack of data or subsequent analyses to confirm whether some predictions stated in the EIS were correct, or not, 14 or 47 percent of the outcomes, are essentially unknown. Excluding outcomes that are unclear, then the remaining predictions in the EIS were correct in 7 out of 16 outcomes, or 44 percent of the categories listed. Mixed outcomes occur in 4 out of 16, or 25 percent of the categories, and failed predictions, occur in 5 out of 16, or 31 percent of the categories. As such, less than 50 percent of the outcomes were predicted correctly, underscoring the uncertainties associated with working in a large complex system with few to no long-term data sets. Similar uncertainties are faced by all resource managers charged with ecosystem restoration globally. The acceptability of this kind of uncertainty is influenced by interpretation, societal values, agency missions and mandates, and other factors. However, failure to correctly predict the future, in and of itself, is not deleterious under the paradigm of adaptive management where large uncertainties provide opportunities for learning and adjustment through an iterative process of "learning-by-doing" (Walters and Holling, 1990). Although recent science has documented a continued decline of environmental resources of the Colorado River below Glen Canyon Dam, it has also identified options that might still be implemented by managers to achieved desired future conditions in Grand Canyon.

Keywords: Adaptive Management; Colorado River; Grand Canyon; Glen Canyon Dam; humpback chub; Grand Canyon Monitoring and Research Center; sediment; sand.

Introduction

March, 2005 marked the 10^{th} anniversary since completion of the Final Environmental Impact Statement (EIS) on the Operation of Glen Canyon Dam (U.S. Department of the Interior, 1995). The next year, 1996, saw the implementation of the Glen Canyon Dam Adaptive Management Program (AMP) as a means of guiding the operation of Glen Canyon Dam to achieve the objectives outlined in the EIS. Gloss *et al*. (2005) document the first systematic review of the effects of Glen Canyon Dam operations on the natural and cultural resources of the Grand Canyon and thus provide an important milestone for evaluating the success of the program to date. This paper has four objectives: (1) to provide an overview of the Colorado River Basin and Glen Canyon Dam as background to the other objectives; (2) to briefly describe the roles and functions of the Glen Canyon Dam Adaptive Management Program; (3) to discuss lessons learned over the last decade and their applicability to dam management in general; and (4) to discuss opportunities for future research.

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The Colorado River

The Colorado River is one of the most important rivers in the western United States providing water for over 25 million people (Schmit *et al*., 2005). According to information summarized by Blinn and Poff (2005) the basin encompasses over 642,000 km^2 and ranges from 42°N to 32°N latitude. Draining nearly 8% of the land area of the United States, the Colorado River and its 22 major tributaries flow through seven states (Wyoming, Colorado, Utah, Arizona, Nevada, New Mexico, and California), and two countries, including a small part of Mexico.

The river heads at over 3,000 m in the Rocky Mountains of the United States and unregulated flows were driven largely by snowmelt before the construction of Glen Canyon Dam and other dams. Flows through the Grand Canyon ranged from a low of 85 m^3/s in the late summer to about 2,300 m^3/s in the late spring. Flood flows of 8,500 m^3/s were recorded in historical times and flows of greater than 14,160 m^3/s may have occurred in the last 1,600 years. The annual unit area discharge of 29,800 m^3/km^2

or runoff of 2.98 cm/yr gives the Colorado River basin the distinction of being one of the driest in the world (Blinn and Poff, 2005). It is also one of the most regulated and impacted rivers in the world with over 40 large flow-regulation structures and diversions along its length (Blinn and Poff, 2005; Nilsson *et al.*, 2005). Most of the runoff (64%) is used for irrigation and another 32% is lost to evaporation from reservoirs. Additional information on the river is provided by Blinn and Poff (2005) and Topping *et al.* (2003) and the reader is referred there for details beyond those presented in this paper.

The river flows through Grand Canyon National Park creating one of the world's premier river canyons. The park was designated a World Heritage Site by the United Nations Educational, Scientific and Cultural Organization in 1979. Created in 1919, the park encompasses almost 500,000 ha. The canyon is approximately 450 km in length, 24 km across at its widest point, and over 1,800 m deep at some points. In addition to its physical attributes, the canyon has important cultural significance to several Native American tribes (Fairley, 2005).

Glen Canyon Dam

Construction of Glen Canyon Dam began in 1957, and the last bucket of concrete was poured in 1963. The concrete arch structure is 216 m high and impounds an approximately 300 km long, 65,315 ha reservoir named Lake Powell. The storage capacity of Lake Powell is about 3.42×10^{10} m^3. Eight generating units are fitted at the dam with a combined output of about 1.3 million kilowatts (Bureau of Reclamation, 2006). These units are typically operated to meet "peaking" electrical demand in the southwestern U.S., with diurnal releases ranging from about 142 to 708 cubic meters per second. The dam is situated about 24 km upstream from the eastern boundary of Grand Canyon National Park.

Prior to the construction of the dam the Colorado River in the Grand Canyon was characterized by highly variable flows (see above) and high sediment loads. The volatile nature of the river contributed to regular scouring of the riparian habitat. Water temperatures ranged from a low of about 0° to a high of about 29°C. The sediment-laden water prevented significant development of aquatic plants and as such, energy inputs into the system were dominated by allochthonous sources such as driftwood and terrestrial leaf litter (Kennedy and Gloss, 2005). This low productivity likely contributed to low species diversity, but the harsh conditions fostered the development of a significant endemic fish fauna. Eight fish species occurred in the Grand Canyon prior to the construction of the dam (Mueller and Marsh, 2002) and four species are now extirpated (see below).

After the construction of the dam, flows were altered significantly by removing most of the seasonal and annual variation that occurred under natural conditions (Topping *et al.*, 2003). Flood frequency was significantly reduced by dam operations. Most variation in the system now occurs on a daily basis to enhance hydropower generation. The dam also traps about 84% of the sand that formerly entered Grand Canyon resulting in discharges of clear water instead of the turbid water that characterized the pre-dam environment. The increased water clarity allows photosynthetic activity to occur in the river bed and large reaches of the river now have energy inputs dominated by autochthonous instream production (Kennedy and Gloss, 2005). However, tributaries below the dam, such as the Paria and Little Colorado Rivers, intermittently add high concentrations of fine sediment to the main channel (Wright *et al.*, 2005). In addition, because the water enters penstocks deep below the surface of the lake before being routed through the turbines, discharges are cold year round ranging from 7° to 12°C (Vernieu *et al.*, 2005).

Post-dam changes in the river environment have not been favorable to native fish populations, while fostering the dominance of non-native fish species (Gloss and Coggins, 2005), especially salmonids (rainbow trout – *Onchorhyncus mykiss* and brown trout – *Salmo trutta*). In addition to these ecological effects of dam operations there have been beneficial effects on recreational river use (Loomis *et al.*, 2005) and water and power uses (Harpman and Douglas, 2005). Additional details on these benefits are provided in the sections on hydropower and recreation below.

Glen Canyon Dam Adaptive Management Program

Glen Canyon Dam was completed before the passage of the U.S. National Environmental Policy Act in 1969 or the Endangered Species Act in 1973. Environmental concerns regarding the dam initially focused on inundation of Glen Canyon upstream from Grand Canyon. However, after construction of the dam was completed, concern mounted over the effects of dam operations on downstream resources in Grand Canyon National Park. Apprehension regarding the environmental effects of the dam led to a series of environmental studies from 1982 through 1996, passage of the Grand Canyon Protection Act in 1992, and ultimately, completion of the Final EIS and Record of Decision in 1995 and 1996 (U.S. Department of the Interior, 1995, 1996), respectively (see Schmit *et al.*, 2005; Stevens and Gold, 2003 for more details on the evolution of the program).

All of the alternatives considered in the EIS recommended the implementation of "adaptive management" as a framework for dam management, and the Record of Decision institutionalized that approach when the preferred alternative (Modified Low Fluctuating Flows [MLFF]: see Table 1 for defining parameters) was selected. The EIS (U.S. Department of the Interior, 1995) states:

> "It is intended that the ROD [Record of Decision] will initiate a process of 'adaptive management,' whereby the effects of dam operations on downstream resources would be assessed and the results of those resource assessments would form the basis for future modifications of dam operations. Many uncertainties still exist regarding the downstream impacts of water releases from Glen Canyon Dam. The concept of adaptive management is based on the recognized need for operational flexibility to respond to future monitoring and research findings and varying resource conditions."

Table 1 Operating limits and general likelihood of occurrence under the preferred alternative (U.S. Department of the Interior, 1995) of Modified Low Fluctuating Flows. Conditions are based on operating rules constrained by annual hydrology.

	General Range of Hydrologic Conditions for Glen Canyon Dam		
	Dry (minimum of 8.23–10 Million Acre Feet of annual release)	Normal (10–15 Million Acre Feet of annual release)	Wet (15–20 Million Acre Feet of annual release)
Minimum releases 7a.m.–7 p.m. (cfs)	8,000 (likely only during weekends)	8,000 (unlikely to occur)	8,000 (very unlikely to occur)
Minimum releases 7p.m.–7 a.m. (cfs)	5,000 (very likely to occur on weekends)	5,000 (unlikely to occur)	5,000 (very unlikely to occur)
Maximum Peak under diurnal releases (cfs)	25,000 (daily peaks reach about 18,000–19,000 cfs, mainly during summer)	25,000[1] (daily peaks reach about 20,000–24,000 cfs, mainly during summer)	25,000 (steady flows at this level occur for 1.5 MAF monthly releases)
Daily fluctuations (cfs/24 hrs)	5,000 6,000 (all possible) 8,000[2]	5,000 (unlikely) 6,000 (possible) 8,000[3] (Most Likely)	5,000 (unlikely) 6,000 (unlikely) 8,000[4] (most likely)
Ramp rate (cfs/hr)	4,000 up (always) 1,500 down (always)	4,000 up (always) 1,500 down (always)	4,000 up (always) 1,500 down (always)
Monthly volume (Million Acre Feet)	480,000–900,000	700,000–1,200,000	800,000–2,000,000

[1]Exceeded during habitat maintenance flows.
[2]Maximums represent normal or routine limits and may necessarily be exceeded during high water years.
[3]Maximums represent normal or routine limits and may necessarily be exceeded during high water years.
[4]Maximums represent normal or routine limits and may necessarily be exceeded during high water years.

Thus, the Glen Canyon Dam Adaptive Management Program (AMP) was created. Adaptive management within the context of Glen Canyon, (1) embraces a relatively new paradigm of natural resource agencies governing with input from stakeholders; (2) recognizes the uncertainty associated with agency decisions and policies; (3) allows stakeholders to make formal recommendations to the U.S. Secretary of the Interior via a Federal Advisory Committee; and (4) places a premium on stakeholders developing a shared vision.

The structure of the AMP is shown in Figure 1. Ultimately, the U.S. Secretary of the Interior has statutory responsibility for controlling water on the Colorado River. The Federal Advisory Committee is called the Adaptive Management Work Group (AMWG) and is comprised of 24 members (Table 2) and a Chair designated by the Secretary of the Interior. AMWG members focus on policy issues and make their recommendations on dam operations to the Chair who, in turn, communicates them to the Secretary for final decisions on workplans, funding, experimentation, etc. In turn, each AMWG member has a technical representative in the Technical Work Group (TWG) that interfaces with the science components of the program.

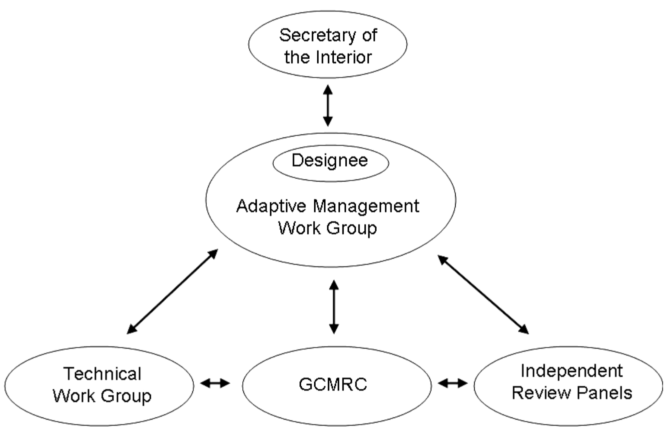

Figure 1 Organizational structure of the Glen Canyon Dam Adaptive Management Program modified from Stevens and Gold (2003). The Designee refers to the Chair of the Adaptive Management Work Group established by the Secretary of the Interior. GCRMC refers to the Grand Canyon Monitoring and Research Center of the U.S. Geological Survey. Refer to text for additional details.

The primary science provider for the AMP is the U.S. Geological Survey, Grand Canyon Monitoring and Research Center (GCMRC). Created in 1995, the Center facilitates research and monitoring in the program and communicates their findings to the program in briefings, publications (e.g., Gloss *et al.*, 2005) and symposia. The mission of the GCMRC is to provide credible, objective scientific information to the Adaptive Management Program on the effects of operating Glen Canyon Dam on the downstream resources of the Colorado River ecosystem, utilizing an ecosystem science approach

Independent Review Panels comprised of academics with expertise germane to the program, are convened periodically to provide peer review and quality control as needed. Included under this Panel is a standing Science Advisory Board that works with the TWG and GCMRC to bring recommendations and information to the AMWG at regular meetings. Meetings are posted in the U.S. Federal Register and are open to the public.

Lessons learned in over a decade of research and monitoring

After more than a decade of research and monitoring a systematic review of the impact of dam operations on natural and cultural resources in Grand Canyon was published (Gloss *et al.*,

Table 2 Stakeholders in the Glen Canyon Dam Adaptive Management Program with membership on the Federal Advisory Committee known as the Adaptive Management Work Group.

Cooperating agencies
1. Bureau of Reclamation
2. U.S. Fish and Wildlife Service
3. Department of Energy
4. Bureau of Indian Affairs
5. National Park Service
6. Hopi Tribe
7. Hualapai Tribe
8. Navajo Nation
9. Southern Paiute Consortium
10. Pueblo of Zuni
State agency
11. Arizona Game & Fish Department
Environmental Groups
12. Grand Canyon Wildlands Council
13. Grand Canyon Trust
Recreation Interests
14. Grand Canyon River Guides
15. Federation of Fly Fishers
Basin States
16. Arizona
17. California
18. Colorado
19. Nevada
20. New Mexico
21. Wyoming
22. Utah
Federal Power Purchase Contractors
23. Colorado River Energy Distributors Association
24. Utah Associated Municipal Power

2005). One of the goals of this compilation was a review of the predictions contained in Table II-7 of the EIS (summarized in Table 3). The table contains a list of resources and associated predictions on how those same resources would respond under the preferred alternative. An expanded list of predictions in a slightly different time scale is given in Schmidt *et al.* (1998).

During preparation of the EIS, the best scientific data were used to generate those prognostications. From the precipice of time, a decade later, we have significant new information to use in evaluating the dam's re-operation relative to objectives of the 1995 EIS, and the 1992 Grand Canyon Protection Act. In this section we will summarize what we have learned about the Colorado River ecosystem from the perspective of over a decade of scientific inquiry, and discuss challenges facing continued research and monitoring in support of the Glen Canyon Dam Adaptive Management Program (AMP).

Integrated Quality-of-water – The presence and design of Glen Canyon Dam have caused major environmental changes to the Colorado River ecosystem including: (1) alterations in the timing and variability of the river's annual, season and daily flow patterns, (2) drastic reduction of the sand supply to the Glen, Marble and Grand Canyon reaches and (3) reduced annual variability in temperature. On the basis of current science information, the MLFF operating alternative has not effectively mitigated the influence of regulation with respect to either the thermal and hydrologic changes, or the sand supply limitation of the downstream ecosystem.

Detailed monitoring of water quality throughout Lake Powell spans a period of about 40 years, making this one of the most robust monitoring efforts conducted under the AMP. These data coupled with downstream temperature data provide rich opportunities for the limnological modeling of the reservoir; an effort that is currently underway. Given the importance of Lake Powell as the major source of water for the Colorado River ecosystem below, this monitoring program serves as an early warning system for changes in quality-of-water.

While the information on the reservoir briefly summarized by Vernieu *et al.* (2005) has shown that dam operations have affected some resources downstream from Glen Canyon Dam, water quality in this large reservoir appears to be largely unaffected by the new dam operations since 1991. However, the reservoir does have the potential to exert substantial impacts on downstream resources. For example, the current drought that started in 2000, reduced the level and volume of Lake Powell to elevations not seen since the reservoir was initially filling in the late 1960's. The lower reservoir storage level has brought warmer surface (epilimnetic) waters to the penstocks causing increased water temperatures to be discharged into the canyon. In addition, continued reservoir drawdown has resulted in the re-suspension of large amounts of deltaic sediment in the reservoir. The organic material contained in this sediment caused a decrease in oxygen concentrations in the reservoir that could potentially be discharged downstream.

Overall, the water quality of the reservoir appears to be more strongly linked to climatic annual to decadal variability governing spring inflow events, protracted swings in upper Colorado River Basin hydrology and by continuing depletions basin-wide, than it is by the re-operation of the hydropower plant over the last decade under the preferred alternative (MLFF). This is true because the Record of Decision did not change Long-Range Operating Criteria tied to mandatory transfers from Upper to Lower Colorado River Basin states. However, periodic release of short-duration spills that bypass the hydropower plant (controlled floods, termed "Beach-Habitat Building Flows") are one element of the current Record-of-Decision that does have an immediate influence on the structure of the reservoir. The changes appear related to the fact that such releases are made from outlet works at depths beneath the power plant intakes where temperatures and oxygen levels tend to be lower. Potentially, releases made from higher elevations in the reservoir (by means of a Selective Withdrawal Structure [SWS]) would also change reservoir characteristics, but with uncertain influence on the downstream ecosystem, particularly with warmer discharges.

The effects of warmer water on downstream biological resources are difficult to predict with certainty and potentially

Table 3 Natural and cultural resources of the Colorado River ecosystem and predictions from the Final Environmental Impact Statement (EIS) for the Operation of Glen Canyon Dam (U.S. Department of the Interior, 1995) on how they would respond under the preferred alternative of Modified Low Fluctuating Flows. Resources are ordered as they appear in the EIS. Symbols are as follows: a plus sign (+) indicates that prediction was correct or exceeded expectations, a minus sign (−) indicates that the prediction was not entirely correct or did not achieve the desired outcome. A "plus" and "minus" (+/−) sign together indicate a mixed outcome. Data unavailable may imply a total absence of data or that the data are not available to the USGS, GCMRC through the scope of their research and monitoring program.

Resource	Prediction	Outcome	Comments
SEDIMENT & AQUATICS			
Fine sediment (sand bars and related physical habitats linked to native fishes [backwaters], terrestrial vegetation, marshes, campsites for recreation and *in-situ* preservation of archeological resources).	Modest improvement through implementation of constrained daily power plant operations and periodic implementation of Beach-Habitat Building Flows following accumulation of new tributary sand supplies in the main channel of the ecosystem. Sand accumulation was predicted to occur under average-to-below average hydrology and associated hydropower operations.	−	Sand bars continued to erode and new sand inputs were not accumulated within the main channel. However, Beach-Habitat Building Flows were allowed. Flexibility in the timing and frequency of these controlled floods limited their effectiveness
Coarse sediment[5] (debris flow impacts from tributaries and their influence on the navigability of rapids and terrestrial sand bars).	Inputs of coarse-grained sediment from tributary debris flows will continue to accumulate in the main channel under constrained hydropower operations, causing rapids to worsen and burying sand bars under coarse deposits. High flow releases may partially rework the new deposits and improve navigation within rapids.	+	The influence of ongoing, naturally occurring debris flows, in terms of aggradation of rapids and burial of sand bars, has been partially mitigated by occasional Beach-Habitat Building and Habitat-Maintenance Flows. The ability of high dam releases to rework new debris flow deposits is related more to peak discharge and timing after debris-flow events than it is related to duration of the high releases
Aquatic food web	"Potential major increase"	±	Apparently increased in Lees Ferry reach, but not necessarily canyon-wide, as fine-sediment inputs from tributaries below this reach are most likely limiting factor in primary productivity
Native fish	"Potential minor increase"	±	Decrease in adult humpback chub, native suckers may be stable or slightly increasing
Non-native fish	"Potential minor increase"	+	Rainbow trout population increased substantially following the operational change in the Lees Ferry reach and within Marble Canyon.
Interactions between native and non-native fish	"Potential minor increase in warm, stable microhabitats"[6]	−	Exception owing to drought-lowered Lake Powell levels not directly related to dam operations
Trout	"Increased growth potential, stocking-dependent"	−	Rainbow trout numbers have increased in the Lees Ferry reach, body condition has declined, and stocking is not required
VEGETATION			
Woody plants	Modest increase[7]	+	There has been a significant increase, especially arrowweed and non-native tamarisk in the riparian zone that was formerly inundated frequently under the "No-Action" hydropower operation
Emergent marsh plants	"Same as or less than no action"	−	Reduction in wet marsh species with an increase in dry marsh species, likely owing to the accumulation of fine sediment in these areas through time, but without periodic rejuvenation through floods.
WILDLIFE			
Wintering waterfowl	Potential increase	+	(Need comment here)

Table 3 (*Continued*)

Resource	Prediction	Outcome	Comments
ENDANGERED AND OTHER SPECIAL STATUS SPECIES			
Native fish (humpback chub, razorback sucker, flannelmouth sucker)	"Potential minor increase"	±	Decrease in adult humpback chub, native suckers may be stable or slightly increasing
Bald eagle	"Potential increase"	?	Eagle numbers in Arizona have increased overall
Peregrine falcon	No effect	+	Stable in Grand Canyon since 1988
Kanab ambersnail	"Some incidental take"	±	Snail habitat increased since 1998, but not snail numbers which are relatively stable
Southwestern Willow Flycatcher	"Undetermined increase"	−	No increase. Uncommon in Grand Canyon.
CULTURAL RESOURCES			
Archaeological sites affected	"Moderate (Less than 157)"	?	Subsequent analyses have not been conducted to fully assess
Traditional cultural properties affected	"Moderate"	?	Subsequent analyses have not been conducted to fully assess
Traditional cultural resources affected	"Increased protection"	?	Subsequent analyses have not been conducted to fully assess
AIR QUALITY			
Effect of emissions on regional air quality	"Slight reduction"	?	Data unavailable
RECREATION			
Angler safety	"Moderate improvement"	?	No long-term monitoring data
Day rafting (navigation past 3-mile bar)	"Major improvement"	?	Pre-EIS study suggests net willingness-to-pay values insensitive to flows. More studies needed
White-water boating safety	"Minor improvement"	?	No long-term monitoring data
White-water boating camping beaches (average area at normal peak stage)	"Minor increase"	−	Camping areas have been diminished owing to vegetation expansion and sand bar erosion, despite the fact that the new operating policy has limited daily peaking release to 25,000 cfs
White-water boating wilderness values	"Moderate to potential to become major increase"	?	Potential decrease and decline in campable area
Economic benefits (not related to hydropower revenue)	Positive	+	Both local and regional impacts
POWER			
Annual economic cost (forgone hydropower revenue)	Acceptable costs relative to other alternatives	?	Subsequent studies not available to fully assess
Wholesale rate of power	Acceptable costs relative to other alternatives	?	Subsequent studies not available to fully assess
Retail rate of power (70% of end users)	"No change to slight decrease"	?	Subsequent studies not available to fully assess
Retail rate of power (23% of end users)	"Slight decrease to moderate increase"	?	Subsequent studies not available to fully assess
Retail rate of power (7% of end users)	Acceptable costs relative to other alternatives	?	Subsequent studies not available to fully assess
NON-USE VALUE	"No data"	+	Substantial non-use value ($3-4 billion) has been demonstrated

[5]This resource was not included in Table II.7 of the EIS but predictions regarding the fate of this material were given on pages 104–105 of the document. It is included in this tabulation for the sake of completeness but the outcome is not included in the percentages discussed in the text.

[6]This would favor native fish and non-native warm water fish.

[7]Exotic species included (tamarisk, camelthorn).

include both positive and negative ecological consequences. Possibilities include allowing for mainstem spawning of native fish, allowing the invasion and dominance of warmwater fishes from Lake Mead and the Little Colorado River, possible adverse alteration of the food base, and uncertain effects on the coldwater fishery in the Lees Ferry reach. The "natural" warming of Glen Canyon Dam releases owing to falling reservoir levels provides an important opportunity to test system responses preceding installation of a SWS on the dam. In addition, lower reservoir storage levels are contributing to increased salinity in discharges. Continued monitoring of both the reservoir and downstream quality of water in the river ecosystem will be required to mitigate any adverse impacts associated with dam operations under continued drought conditions. Linking reservoir processes to downstream quality of water parameters is a high priority for future research and monitoring, especially as related to native and non-native fish interactions, recruitment success in humpback chub and dynamics associated with the food base of the river. An annual to decadal-scale synthesis of the forty-year time series for Lake Powell quality of water is a next essential step in the research program.

Climate and drought – The preceding section on water quality monitoring in Lake Powell underscores the effect of putative short-term climate trends on limnological parameters. Current understanding of global climate drivers provides little ability to predict the timing or extent of droughts over much of the Colorado River Basin (Webb *et al*., 2005). Data from tree rings suggest that multi-decadal droughts are not unknown in the basin and the organisms and natural processes that developed in Grand Canyon evolved in response to such natural variation. While the current drought may not be a so-called "megadrought" because of the limited duration to date, only time will tell when it ends. Research is needed to improve the ability to forecast climate in the Colorado River Basin. Jain and others (2005), have recently reported a late 20^{th} century trend toward increasing annual variation in streamflow within the large river basins of the western U.S., including the Colorado River. They also report an increasing synchroneity in the response of these western river basins over the same period since the 1970's when water use in the southwestern U.S. began to accelerate. If such a trend persists, then the challenges associated with simultaneously managing water supplies and maintaining environmental resources of the arid southwest will likely only increase through time under increasing depletions and forecast uncertainties (Pulwarty and Melis, 2001).

Mitigating the influence of protracted drought was initially the main objective for constructing Glen Canyon Dam. This was achieved by locating the dam at a site that maximized the storage capacity of Lake Powell. The vast storage volume of the reservoir (about 3.42×10^{10} m^3), provides a time buffer of up to several years against periods of below average runoff in the upper basin. This storage capacity is of immense benefit to upper Colorado River Basin states faced with the challenge of simultaneously pursuing development, while also needing to meet the water supply needs of downstream users. The strategy of maximizing water storage above Glen Canyon Dam is also of interest environmentally in that it is effective at mitigating the ecological role that drought plays in the Colorado River ecosystem below the dam. For instance, operation of the dam without a sediment bypass system or SWS means that the river's flow and sediment-transport capacity are increased on average (Topping *et al*., 2003). However, the thermal regime of the river now hovers somewhere between the conditions that occurred in the pre-dam era between winter and summer, while the currently diminished sediment load is representative of a pre-dam mega-drought with respect to tributary sand production. These limitations in the dam's operation appear to greatly limit options for achieving environmental objectives related to restoration and sustainable management of unique aquatic and terrestrial parts of the Grand Canyon's riverine landscape.

Hydropower production – As the preceding two sections have demonstrated, climatic variability and its affect on hydrologic conditions can have large, if not overriding, effects on resources of concern to the AMP. Hydropower is also a highly valued resource of concern to society and environmental constraints on dam operations under the MLFF policy have large annual economic costs (see Harpman and Douglas, 2005). The acceptability of those costs has to be interpreted within the context of societal values which abruptly shifted away from a focused policy of resource development toward one where preservation of natural resources is increasingly valued. This shift in values occurred only after river regulation was underway. Loomis *et al*. (2005) demonstrated that dam operations benefited both local and regional economies through stabilization of flows relative to pre-EIS and pre-dam conditions, which in turn facilitated the development of a significant industry associated with white-water rafting (see recreational use and non-use section below). Significant non-use values add to the economic value of the Grand Canyon experience regardless of whether respondents visit the canyon or not. A detailed *ex-post facto* cost-benefit analysis of Glen Canyon Dam operations will ultimately be needed to fully assess the MLFF operation versus documented environmental benefits. Such assessments are also needed to fully evaluate any consideration of additional experimental designs or to eventual implementation of any alternative, longer-term changes in the current operating strategy intended to achieve management goals.

Fine sediment – The much hoped for outcome of modest improvement in sand bar resources, as originally proposed and predicted in the EIS, has not been realized (Table 3). Detailed synthesis studies of sand inputs and outputs to the system (sand mass balance), intensive field monitoring, and remotely sensed change detection analyses all point to a decrease in fine sediment resources in Glen, Marble and Grand Canyons in the post-EIS era. These changes have resulted in smaller and coarser-grained sand bar deposits, particularly in the upper reaches of the ecosystem where sand supply is most limited. Loss of sand habitats in the ecosystem was documented under the No-Action era (1964–1990), but has continued since dam operations have been altered to mitigate sand bar erosion. Sand export appears to be driven primarily by the annual strategy of patterning monthly release volumes within MLFF to match seasonally varied regional water supply in the west, variation in seasonal power demands and benefits related to economics of daily "load-following."

Sand-transport data collected from 1999 through 2004, indicate that whenever the monthly flow regime from the Glen Canyon Dam forces daily peak discharges above 10,000 cfs for extended periods, such operations tend to export newly input sand from downstream tributaries and pre-existing sand storage in the main channel relatively quickly. Sediment transport calculations during the EIS substantially under-predicted the capacity of such operations to export new sand inputs and instead predicted that average to below average MLFF operations would allow new sand supplies from tributaries below the dam to accumulate through time over multiple years. Such accumulated inputs were then the basis for predicting that periodically released Beach-Habitat Building Flows would result in sustainable sand bar restoration. Unfortunately, even during years of minimal release hydrology (8.23 million acre feet volumes released from 2000–2004), such exporting flow peaks of 18,000 to 20,000 cfs are a frequently occurring phenomenon in both winter and summer months that annually limits accumulation of new sand supplies from tributaries (Rubin *et al*., 2002; Topping *et al*., 2000a, b; Topping *et al*., 2006; Wright *et al*., 2005).

Although MLFF limitations on the daily allowable peak discharge were intended to reduce sand export and bar erosion, it appears that the annual pattern of monthly volumes released from the dam (with peak daily flows at their highest during the summer sediment input months of July and August) is the greatest factor preventing accumulation of new sand inputs from tributaries over multi-year time scales. Despite minimum allowable annual volumes of water released from Glen Canyon Dam during 2000–2004 (8.23 million acre feet), sand inputs from the Paria and Little Colorado Rivers were quickly transported downstream during months in which release schedules forced daily peaks to between 18,000–20,000 cfs. Owing to this, the greatest factor limiting Beach-Habitat Building Flows in achieving habitat restoration is tied to condition of sand supply limitation that persists from year to year, even during continuous, multi-year drought conditions in the Upper Colorado River Basin and below average MLFF operations. While the seasonally adjusted pattern of monthly releases during a prolonged drought provides significant economic benefit to some stakeholders in terms of hydropower revenues, these benefits apparently come at the expense of environmental goals tied to downstream sand resources and related habitats.

Since closure of Glen Canyon Dam has eliminated about 84% of the sand that historically entered Grand Canyon, managing the remaining supply below the dam will apparently require careful prescription of managed BHBF's, strategically released immediately following natural sand inputs. It is not yet clear whether even this strategy will succeed in sustainable restoration of sand resources throughout Grand Canyon (Topping *et al*., 2006; Rubin *et al*., 2002). In essence, efforts to restore sand bars without sufficient sand supplies are analogous to attempting to restore a bankrupt financial system with modest infusions of interest rather than substantial investments of principal. Since physical processes related to hydrology and sediment transport are relatively well studied, a logical question is why the writers of the EIS predicted this outcome incorrectly? Again, the EIS writers used the best science that was available, but three critical monitoring programs for measuring suspended-sediment flux throughout the Canyon were discontinued in the early 1970's, forcing the EIS team to evaluate a discontinuous set of post-dam transport data and then work with flawed assumptions rather than continuous data records of flow and sediment concentration. Clearly, long-term core monitoring efforts are essential to the success of adaptive management and accurate predictions.

The EIS assumption that sand would accumulate on the bed of river over multiple years is now known to be flawed. Our research suggests that future management of sediment should involve high flow releases immediately following inputs of sand and finer sediment from tributaries below the dam. While such releases are controversial in that they must bypass the hydropower plant, recent studies also suggest that the duration of such flows may need to be only a small fraction of what was originally suggested. Such fine tuning in the prescription of controlled floods used for achieving habitat restoration (Stevens *et al*., 2001) will likely reduce the financial impacts and controversy associated with such management actions. One alternative test of the MLFF concept for multi-year accumulation of sand supply might be to equalize monthly volumes during droughts so as to further limit daily peaks over such periods. If such a test failed to increase sand supply through multi-year accumulation of tributary sand inputs, then objectives for sand habitat restoration might have to be reconsidered, or more proactive strategies, such as sediment augmentation, might need to be implemented.

Coarse sediment – This resource was not included in Table II-7 of the EIS but is included because of its importance to the overall ecological condition of the river in Grand Canyon. In contrast to fine sediment, coarse sediment inputs have largely been unaffected by the presence or operation of Glen Canyon Dam. This owes to the presence of hundreds of unregulated tributary canyons along the length of Grand Canyon that contribute coarse sediment to the system. However, with the erosion of fine sediment from the system (see above) tied to dam operations under Modified Low Fluctuating Flows, an overall sediment trend for the Grand Canyon reach has been coarsening of the substrate in the river channel, as fines are eroded, leaving gravel and larger material. The impact of this "coarsening" of the river substrate has two profound biological implications. First is the creation of preferred habitat for benthic invertebrates, an important component of the food base. Second, is the creation of spawning substrate for the non-native rainbow trout. Both of these changes move the system farther from pre-dam conditions, potentially benefiting non-native species at the expense of natives.

Inputs of coarse sediment are largely localized and episodic, triggered by local storm events and rockslides (Webb *et al*., 2005). When debris flows occur, they contribute to the existing system of rapids for which Grand Canyon is famous by restricting channel width in outwash areas. Under regulated flows associated with Glen Canyon Dam operations, floods above 45,000 cfs are now extremely rare in the Canyon. As a result the river no longer has the power to rework coarse sediment deposits in rapids to the extent possible before construction of the dam. It is possible that some rapids will increase in size owing to regulated flows. Research is needed to determine if high spike flows from the dam would be effective at reworking coarse sediment deposits periodically to mimic unregulated conditions.

Aquatic food base – Prior to the construction of the dam, the sediment-laden waters of the Colorado River continually scoured river bottom habitats and permitted little light penetration, both of which strongly limited the growth of algae and other aquatic plants. Most of the nutrients and energy that entered Grand Canyon arrived as drift from sources outside the river. These external inputs of energy arrived in the form of leaf litter, coarse woody debris, and other materials carried down from terrestrial sources or upstream tributaries. Following completion of Glen Canyon Dam, water discharged downstream was cold and clear, as described in the section on Quality of Water. This clear water allowed for the development of a substantial food base dominated primarily by algae and aquatic plants, thus changing the dominant energy inputs from external sources to instream production. The plentiful algae in the post-dam Colorado River support a high density of invertebrates (Kennedy and Gloss, 2005).

As one goes downstream from the Lees Ferry tailwaters, tributary inputs of sediment limit light penetration, and hence photosynthesis, causing abrupt decreases in algae standing mass and a transition back towards the dominance of external energy sources. Invertebrates communities also shift with this transition in energy sources, and filter-feeding invertebrates that capture fine particles of leaf litter and other detritus appear to dominate downstream reaches. However, the biomass of invertebrates appears to also decrease with downstream distance, perhaps because there is less energy available in the system due to the reduction in algae standing mass. Considerable research is still needed to better understand the effects that dam operations and episodic inputs of sediment from tributaries have on the food base across the entire Colorado River ecosystem.

Dam operations under MLFF probably led to increases in the standing mass of food base resources (i.e., algae and invertebrates) due to steadier flows and greater minimum discharges of clearer water (Table 3). However, declines in humpback chub populations since implementation of MLFF suggest this change in the aquatic food base may have not necessarily benefited native fish that evolved in the turbid waters that characterized the pre-dam environment.

A critical future research need is to develop a better understanding of the linkages between the food base and the actual prey base of fish, both native and non-native. A large amount of data have been collected on the food items consumed by non-native rainbow and brown trout, but comparable data are not available for the humpback chub due to the endangered status of this fish. Use of stable isotope analysis will be critical to assessing the energy sources and trophic pathways that are importance to fish. Additionally, critical tests of the hypothesis that competition between non-native trout and humpback chub is negatively affecting humpback chub populations are not available. Eating the same food items is only the first criteria to establish that competition is negatively impacting a particular species. For competition to have a negative impact on a species, overlapping resources must also be limited and one species must be more efficient at harvesting the limited resources than another. In the food-rich environment of the post-dam Colorado River, the second criteria may not be a reasonable assumption. Further research will be required to determine if this hypothesis is supported by data.

Fish – Eight species of native fish were found in the Grand Canyon prior to the modern era. Most of these were endemic to the Colorado River system making this one of the most unique fish communities in the world (Mueller and Marsh, 2002). Of those, only four remain including the humpback chub, the bluehead sucker, the flannelmouth sucker and the speckled dace. Gone are the razorback sucker, bonytail, roundtail chub and the Colorado pikeminnow, all of which survive outside of Grand Canyon. The humpback chub is endangered and its numbers have dropped dramatically in the last decade. At the same time, non-native fish have increased in both diversity and abundance.

The reasons for the decline of native fish are commonly cited to include the construction and operation of numerous dams on the Colorado River, the introduction of non-native predatory and competitive fishes, and the introduction of diseases and parasites (Mueller and Marsh, 2002). The actual mechanisms of decline and extirpation are poorly known owing to a lack of early data on population numbers and the fact that declines were well established prior to construction of major dams (but not prior to the introduction of exotic species).

Our knowledge of the effect of dam operations on native fish is incomplete, but there is only a limited body of evidence that Modified Low-Fluctuating Flows have been beneficial to the survival and recruitment of humpback chub, to support the prediction of the EIS (Table 3). However, we do not know if the overall adult decline of chub, and the recent evidence of recruitment and flattening of the population trend during the decade of operations under this regime is attributable to Modified Low-Fluctuating Flows *per se* (Gloss and Coggins, 2005; Coggins *et al*., 2006a; Melis and Coggins, in review). Mechanical removal of non-native fish, especially rainbow trout is currently in the fourth year of a four year implementation strategy to test the hypothesis that reduction of predatory and competitive fish species will result in an increase in survival and recruitment of humpback chub. While the GCMRC has demonstrated that mechanical removal is an effective way to significantly reduce the number of non-native trout in the removal reach (Gloss and Coggins, 2005), fishery scientists are still collecting the data required (2003 and beyond) to evaluate the hypothesized response in humpback chub. Given our knowledge of the life history of the chub, a signal is not expected for four or five years after the initiating of mechanical removal efforts.

In contrast to recent decline in the abundance of adult chub, populations of both bluehead and flannelmouth suckers appear to have remained relatively stable under the current flow regime of Modified Low Fluctuating Flows. The reasons for this persistence are currently unknown. On the other hand, the relatively stable habitat conditions created under Modified Low Fluctuating Flows, coupled with a coarsening of substrate in the river channel (see above section on fine sediment), appear to have greatly favored rainbow trout, particularly in the Lees Ferry reach, as reflected in their increasing numbers during the last decade.

In addition to establishing better linkages between our knowledge of the food base, dam operations, and fish populations, we need to focus future research on the effects of warming discharges of water from Glen Canyon Dam. An SWS is anticipated to be installed on the dam sometime later in this decade and substantial questions remain unanswered on its effects. Will the SWS warm water temperatures to a point where main channel spawning of humpback chub is possible? Will young native fish emerging from natal habitat in the Little Colorado River be able to survive and grow in the warmer waters? Will the tailwater trout fishery below the dam remain healthy and viable? Will new diseases, parasites and invasive species become established in warmer habitats? Will warmwater predatory fish from downstream establish themselves as dominant species in the Grand Canyon fish community? Will non-native trout in the Little Colorado River/main channel confluence decrease in abundance as a result of increasing temperatures? These are all critical questions that must be answered in the near future.

Terrestrial vegetation – Dam operations under Modified Low Fluctuating Flows greatly stabilized antecedent and pre-EIS flow conditions in the Grand Canyon with significant impacts on riparian vegetation (Ralston, 2005). The EIS predicted a modest increase in woody vegetation (Table 3) and that prediction is largely correct, if not understated. The EIS also predicted that marsh communities would be the same as or less than expected under the No Action alternative, but that prediction was largely incorrect. Since implementation of Modified Low Fluctuating Flows there has been a decrease in wet marsh vegetation and an increase in dry marsh vegetation.

The pre-dam environment was subject to large variations in flow that regularly scoured shoreline habitats of vegetation, resetting the system after major floods. Scouring flows are now rare adding an element of stability to the system and ultimately affecting plant communities. For example, since daily peaking releases under Modified Low Fluctuating Flows are limited to no more than 25,000 cfs, the old high water vegetation zone is now dependent entirely on incident precipitation for water. This has resulted in some changes to species composition, particularly those species that don't have deep tap roots to reach the water table associated with river flows. Removing access to surface water from desert plant communities, forcing them to rely on incident precipitation only, has been documented to lead to decreases in plant biomass over time (Schlesinger *et al*., 1989).

The stability of flows has also encouraged an increase in vegetation density in and near the wetted zone. While an increase in vegetation may appear to be desirable, one of the impacts is a decrease in available camping area for recreationists (Kaplinski *et al*., 2005). Furthermore, the increase is largely attributable to expansion of non-native saltcedar or tamarisk into the riparian zone, often resulting in a monoculture that is not always beneficial to wildlife (Lovich and de Gouvenain, 1998). However, recent research suggests that moving toward more natural river flow regimes with the use of pulse floods allows native plants species to become established despite the presence of tamarisk (Glenn and Nagler, 2005).

Overall, interim (1991–1996) and Modified Low Fluctuating Flows (1996–2005) have caused a contraction in the extent of the riparian plant community, comprised of more homogeneous (including non-native species) plant assemblages, with more mature individuals. The export of fine sediments from the system is further reducing available substrate for vegetation and marsh vegetation. The effects of large-scale restructuring of riparian plant communities in the Grand Canyon is expected to have cascading impacts on co-adapted animal species, especially neotropical migrant birds. Future research should focus on identifying the responses of animals to this fundamental change in habitat structure, the relationship between riparian vegetation and insects as related to the food web of the river, and examining the affects of human-mediated removal of exotic vegetation vs. natural disturbance.

Birds – Bird monitoring in the Grand Canyon related to the Glen Canyon Dam Adaptive Management Program has been driven by two factors: 1) concern regarding the possible effects of dam operations on sensitive species (e.g., Bald Eagles – *Haliaeetus leucocephalus*, Peregrine Falcons – *Falco peregrinus anatum*, and Southwestern Willow Flycatchers – *Empidonax traillii extimus*), and 2) the perception that birds are good ecological indicators of short-term (post-dam) changes in the canyon. Overall, it appears that birds are neither driving the ecological system in the Grand Canyon, as they do in other ecosystems (Croll *et al*., 2005), nor are their regional population dynamics strongly driven by factors within the canyon. Research has demonstrated only a minimal direct effect of dam operations on most birds. An exception to this generalization is shown for waterfowl that appear to have benefited from the stability of post-dam flows (Table 3) (Holmes *et al*., 2005).

However, at the local level, changes in riparian vegetation, mentioned above, have resulted in increased bird density and diversity in the Grand Canyon. As such, post-dam flows have had indirect effects on the bird community via their more direct effects on plant community structure. Beyond that, it is difficult to relate dam operations to bird dynamics, especially for neotropical migrants. These hemispherical migrants are affected by factors throughout both their breeding and wintering ranges. For example, a decline in Southwestern Willow Flycatcher numbers might be caused by mortality on the wintering range in Central or South American and have nothing to do with impacts in the Grand Canyon, or elsewhere, in the breeding range.

Future bird research and monitoring in the Grand Canyon requires answering some fundamental questions. First, should birds continue to be monitored under the Glen Canyon Dam Adaptive Management Program given the indirect relationship between dam operations and most bird population dynamics? Second, how exactly do dam operations affect plant community dynamics and ultimately birds? Finally, how do vegetation characteristics affect individual bird species?

Special status species – Many of the research and monitoring efforts in the Glen Canyon Dam Adaptive Management Program are necessitated by compliance requirements from various laws, especially the U.S. Endangered Species Act (Ralston, 2005). One species, the Kanab ambersnail, is assumed to be found naturally at only two locations, one in the Grand Canyon and another in southern Utah. Genetic analyses are underway to assess the level of differentiation between Grand Canyon populations and snail populations with similar morphology north of the canyon.

The largest population at Vaseys Paradise is found in the varial zone of dam operations and is thus susceptible to being washed away during rapid changes in flows. In the past, significant efforts have been undertaken to protect snail populations during experimental floods, including temporarily uprooting snail habitat (with snails) immediately before a flood and then returning the habitat at the conclusion of the experimental flow. Despite the vulnerability of such a small species, in such a spatially-limited distribution, snail numbers appear to be relatively stable post-EIS.

With only two breeding pairs of Southwestern Willow Flycatchers present in the Grand Canyon in recent years, efforts to monitor the effects of dam operations on this species are hampered by small sample sizes and issues identified in the section on Birds above. Monitoring efforts should be continued for other rare and special status species to prevent them from declining further and being listed as threatened or endangered species.

Cultural resources – Mass balance studies examining inputs and exports of sand and other fine sediments in the Colorado River ecosystem demonstrate a net export of this resource as a result of dam operations. The sand that is being exported is coming not only from new tributary inputs, but also existing beaches and river terraces that contain archaeological sites. Many archaeological sites in Grand Canyon have been covered with windborne (aeolian) sand for centuries. This sand was transported from lower-elevation beaches that were frequently re-supplied with new sand sources derived from annual floods during the pre-dam era. Following dam closure in 1963, operations were optimized for maximum water storage and power revenue (within the constraints of existing law and policies), rather than for strategically conserving limited downstream remaining sand supplies for restoration of sand bars (and presumably, long-term preservation of cultural sites). With more sand continually leaving the ecosystem than being supplied, more and more of these preservation sites are being exposed to the ravages of erosion. As sites are eroded, artifacts and structures are increasingly exposed, where they become susceptible to visitor impacts and destabilization due to loss of the surrounding sedimentary matrix. Such changes make it difficult, if not impossible for archaeologists to reconstruct and interpret the historical and cultural information contained within these important settings in Grand Canyon National Park (Fairley, 2005).

Future research and monitoring of cultural resources needs to focus on the effects of all components of the MLFF dam operations, most specifically, how the monthly pattern of annual releases might be revised to more effectively influence conservation of new sand inputs from tributaries so as to mitigate the current, continuous fine-sediment deficit.

Recreational use and non-use values – One of the resources that appear to have benefited most from the stabilizing influence of Modified Low Fluctuating Flows, relative to more variable dam operations, is recreational use of the river. By eliminating very high and very low discharges conditions, flows that favor year round recreational boating and fishing are fostered. Although the most comprehensive regional economic study of recreation is now 10 years old (Douglas and Harpman, 1995), the figures are impressive: over $46 million in non-resident total expenditures and maintenance of 586 jobs, with 438 jobs in commercial rafting alone. Presumably those figures are even higher now (Loomis *et al*., 2005).

Based on data collected over 10 years ago, non-use values, or estimates of the "existence" value of Grand Canyon National Park, Glen Canyon National Recreation Area, tribal lands, and the resources therein, to citizens who may never actually engage in recreational activities in the area, are estimated at $3–4 billion (Loomis *et al*., 2005). The public at large is willing to pay to have flows and other management actions that benefit the canyon and its resources. While some may question the utility of non-use valuation of Grand Canyon resources, the estimates reflect the iconic values that make Grand Canyon National Park famous throughout the world.

Future research should focus on detailed analyses of how Glen Canyon National Recreation Area fishing use, catch rates and fish condition are related to flows. Economic data on fishing and recreational rafting also need to be updated to establish current baseline data before new flow regimes are initiated. Finally, studies to quantify the wilderness experience of recreationists need to be initiated so that the benefit of eventually achieving ecosystem restoration can be fully evaluated.

Campsites – Since the implementation of Modified Low-Fluctuating Flows, there has been about a 15% per year reduction in campable area in the Grand Canyon (Kaplinski *et al*., 2005). Losses occurred in both critical (campsite-limited) and non-critical reaches, but the largest losses have occurred in critical areas. Losses are thought to be attributable to both net sediment exports under current dam operations (see section above on fine sediment), as well as encroachment of woody vegetation (see section above on terrestrial vegetation). However, while daily river stage restrictions under the MLFF provide some benefits to campsite area by limiting the varial zone to below 25,000 cfs, camping areas between this upper stage and the former daily limit under the No Action policy (33,000 cfs) have become less accessible owing to vegetation expansion. The exact relationship and interaction between these two factors and dam operations is unknown and provides a challenge for future researchers. For example, increased vegetation in sand bar areas may also provide greater substrate stability and shade, both limiting campsite erosion rates and enhancing camping areas from an aesthetic perspective. Tradeoffs between vegetation expansion and sand bar stability must also be considered from the perspective that increased vegetation might also limit the potential for wind processes to blow sand deposits upslope into cultural preservation sites subject to rainfall and runoff erosion?

How accurate were the 1995 EIS predictions?

The outcomes summarized in Table 3, and presented in the discussions above, present a kind of "report card" to assess the accuracy of predictions that formed the foundation of the Glen Canyon Dam Adaptive Management program, implemented under the EIS with the preferred alternative of Modified Low-Fluctuating Flows. It is important to emphasize that the outcomes listed are based on the best available scientific information and judgment, and are subject to revision as additional information becomes accessible. We attempted to generalize our evaluations in a conservative fashion; details are contained in the original works cited in this paper. With these caveats, we offer the following observations on the ability of current technologies to predict ecosystem, societal and economic responses in Grand Canyon National Park and Glen Canyon National Recreation Area and associated tribal land areas of the ecosystem beyond those boundaries.

Because of a lack of data or subsequent analyses to confirm whether the prediction stated in the EIS was correct, or not, 14 of 30 (excluding coarse sediment: see above), or 46 percent of the outcomes, are essentially unknown at the time of this writing, despite ten years since completion of the EIS. These unresolved outcomes constitute an important list for further study in the program. Correct predications accounted for only 5 outcomes, or 17 percent of the categories listed. Mixed outcomes occur in 6 or 20 percent of the categories, and failed predictions, scored as negative outcomes, occur in 5 or 17 percent of the categories.

Excluding predictions where the outcome is still unknown ($n = 14$), the percentage of outcomes that were correctly predicted (5 out of 16 remaining) is only 31 percent, underscoring the uncertainties associated with working in a large complex system with few to no data sets. Assuming only three categories of outcomes (+, −, or +/−), and that the outcomes are correctly assigned, then the proportion of each outcome mentioned above is not statistically different from an equal probability of any outcome ($\chi^2 = 0.125$, $P = 0.94$). In other words, the ability of the EIS writers to predict the outcome of Modified Low-Fluctuating Flows 10 years latter was, it appears, no better than random chance. A more optimistic approach would be to assign at least a partially successful rating to mixed outcomes (+/−). Under that scenario, 11 out of 16, or 69 percent of the outcomes might be deemed correctly predicted, at least in part. However, this proportion too is not statistically different from random chance ($\chi^2 = 2.25$, $P = 0.13$).

Does this mean that the program is a failure? Not necessarily. The acceptability of this kind of uncertainty is influenced by interpretation, societal values, agency missions and mandates, and other factors (Clark, 2002). However, failure to correctly predict the future, in and of itself, is not deleterious under the paradigm of adaptive management where large uncertainties provide opportunities for learning and adjustment through an iterative process of "learning-by-doing" (Figure 2).

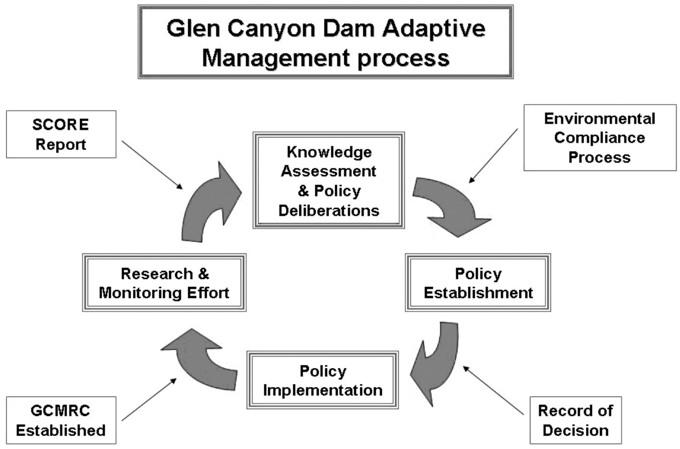

Figure 2 Conceptual illustration of the Glen Canyon Dam Adaptive Management Program process. GCMRC refers to the Grand Canyon Monitoring and Research Center of the U.S. Geological Survey, established as the science provider for the Program. The SCORE report refers to the State of the Colorado River Ecosystem in Grand Canyon publication synthesizing the state of scientific knowledge for the Program (Gloss *et al*., 2005). The next step in the process is knowledge assessment and policy deliberations after which the cycle will continue. Refer to text for additional details.

Future challenges

Sustainable river management involves interrelationships among assessments of ecological risk (Nilsson *et al*., 2005), sustainable management, dealing with uncertainty, adaptive management and decision support (Clark, 2002). While adaptive management with stakeholder involvement is the stated framework for the Final Environmental Impact Statement (U.S. Department of the Interior, 1995) for the Operation of Glen Canyon Dam, it is not without challenges. One of the constraints of the Glen Canyon Dam Adaptive Management Program (AMP) is the artificial prescription of boundaries that extend from the forebay of Glen Canyon Dam to the backbay of Lake Mead, and from the old high water mark on river left, to its counterpart on river right. The definition of the scope of the program is thus largely derived from a human or political perspective. This constraint imposes two important challenges to scientists. First, is the fact that this definition of a boundary does not fully circumscribe natural patterns or processes that affect the Colorado River ecosystem. Others have attempted to define ecosystems on the basis of hydrographic, physiographic, floristic and ethnographic boundaries (Grayson, 1993), all of which present problems in the case of the Grand Canyon. For example, there is no clear floristic definition of the Colorado River ecosystem owing to extremes in elevation and precipitation. By imposing artificial limits on the boundary of the ecosystem, we impose limits on our ability to understand the larger landscape factors that drive physical and thus ecological processes in Grand Canyon.

The second challenge that an artificial boundary presents to scientists is that of restricting research and monitoring activities to the area circumscribed in the definition above, to the exclusion of comparative sites. In the past, researchers in the AMP have been unable to conduct comparative research in river systems less-influenced by high dam operations. For example, Cataract Canyon, Desolation-Gray Canyons, and Westwater Canyon all provide examples in the Upper Colorado River of systems that are more like the pre-dam Grand Canyon than any segment of the river included in the AMP boundary. While there are no rivers or river segments that perfectly match the characteristics of the pre-dam Grand Canyon, important analytical opportunities are lost by not expanding the study to incorporate sites more like a control.

Spatial scope is not the only constraint that presents a challenge to understanding the form and function of the Colorado River ecosystem. Temporal issues operate on scales of over 10 orders of magnitude, ranging from billions of years to minutes, depending on whether one considers the geomorphic framework of the canyon or the hour-to-hour effects of dam operations on that same framework. This extreme variability happens simultaneously, confounding efforts to determine cause and effect. An example is provided by studies directed at understanding the population ecology of the humpback chub. These fish evolved in a canyon that reflects billions of years of geological history, over millions of years of natural selection, with a life span of decades, a time to maturity of 3–5 years, with wide annual pre-dam variation in flows and temperatures, now complicated with daily and hourly variations in flow (but not temperature) post-EIS. The complexity of factors and temporal scales present enormous challenges to effectively determining how population numbers vary in time and space and underscores the importance of long-term studies to describe patterns and processes. Long-lived organisms like the humpback chub require decades to capture population variability related to their life span (Congdon *et al*., 1994).

Another problem, identified in the past, has been a need for greater integration of studies. As the complexity of issues in the Glen Canyon Dam Adaptive Management Program become more obvious, so does the need for interdisciplinary, not just multidisciplinary science. Great progress has been achieved since this issue was highlighted by Meretsky and Melis (1997). Continued efforts will be required to integrate knowledge across disciplines and scales, and develop a more robust conceptual model for the Colorado River ecosystem (Walters *et al*., 2000; Walters and Korman, 1999).

Conclusion

The outcomes of many of the predictions contained in the 1995 EIS are unknown or unsatisfactory. The proportions of outcomes that are correct vs. incorrect are not significantly different from what would be expected by random chance (Table 3). Like predicting the weather, there is a substantial amount of uncertainty, even more, in predicting the ecophysical impacts of dam operations on a large river.

Considerable knowledge has been gained from focused, systematic studies of the Colorado River ecosystem in Grand Canyon. Research, including conceptual and other models (Walters *et al*., 2000; Coggins *et al*., 2006b) and monitoring conducted by U.S. Geological Survey scientists and their cooperators have conclusively demonstrated a net loss of sediment from the system and documented the decline of the federally endangered humpback chub during the last decade. Both findings are critical pieces of information to assess conditions and adjust management actions in the spirit of adaptive management. As in all research, more questions are generated than answers, but those questions form the basis for future studies, another palpable benefit of the program to date. It is also important to note that water delivery requirements continued to be met throughout the decade post-EIS, despite increased costs associated with environmental and experimental regulation of flows.

In an evaluation of a similar Colorado River conservation program, Brower *et al.* (2001) identified several solutions to the problems of consensus-based management (*it is important to note that the AMP is not consensus-based*): (1) program success should be judged by species recovery, (2) the Federal government should retain the ability to impose regulatory sanctions in the event of continued population declines (see also Meretsky *et al*., 2000), and 3) funding should be provided by an agency with clear species-protection responsibilities to reduce the disproportionate influence of utilitarian interest groups. In large measure, these approaches are implemented under the AMP. Just as important, the success of the approach taken to achieve the desired outcomes of the management program should be evaluated against whether or not the actions taken result in ecosystem responses that move in at least the general direction of those stated goals and objectives (Palmer *et al*., 2005). A substantial body of science now exists for the Colorado River ecosystem. The overarching question is, what will society do with the knowledge now available to move into the next phase of the Glen Canyon Dam Adaptive Management Program?

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