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Chapter 13

Lessons from 10 Years of Adaptive Management in Grand Canyon

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Introduction

Almost a decade ago, the Secretary of the Interior issued a Record of Decision (ROD) (U.S. Department of the Interior, 1996) regarding the operation of Glen Canyon Dam and its impacts on natural, cultural, and recreational resources of the Colorado River below Glen Canyon Dam. This decision was largely in response to mandates of the Grand Canyon Protection Act of 1992. Adaptive management (see Overview, this report, for discussion of adaptive management), sometimes known as "learning by doing," was deemed to be the method of choice after a multiyear environmental impact statement process that included extensive public involvement. Practitioners of adaptive management intentionally see management policies as experimental because of the scientific uncertainties inherent in such large, complex ecosystems (Walters and Holling, 1990; Clark, 2002). The intent in selecting this style of management is reflected in the Operation of Glen Canyon Dam Final Environmental Impact Statement (hereafter EIS) with the following language:

> It is intended that the ROD 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 need for operational flexibility to respond to future monitoring and research findings and varying resource conditions (U.S. Department of the Interior, 1995, p. 34).

The very language in the EIS acknowledges that adaptive management is a process of experimentation, monitoring, and evaluation.

The end of a decade of research and monitoring provides an important opportunity to evaluate the effects of Glen Canyon Dam operations on resources of concern and to determine if the desired outcomes are being achieved and whether they are compatible with one another or not. In this concluding chapter we present a summary of adaptive management of the Colorado River ecosystem below Glen Canyon Dam by reviewing predictions contained in the EIS. In table II-7 of the EIS (summarized here in table 1), resource categories are listed and associated with predictions for how those resources would respond under the preferred alternative of modified low fluctuating flows (MLFF) (see table 2 for generalized operating rules). During preparation of the EIS, the best scientific data available were used to generate those prognostications; however, a decade later we have significant new information for evaluating the operation of Glen Canyon Dam in relation to the objectives of the 1995 EIS and the 1992 Grand Canyon Protection Act.

This report is the first systematic attempt to conduct an assessment of the changing state of resources in the Colorado River ecosystem in Grand Canyon over a decadal timeframe. Our objectives are to (1) encapsulate what we have learned about the Colorado River ecosystem over a decade of scientific inquiry, summarizing the most salient conclusions of this report, and (2) discuss, in very general terms, research and monitoring challenges and questions facing the program.

While this report is not meant to be prescriptive with respect to future action for the Glen Canyon Dam Adaptive Management Program, the authors of the preceding chapters presented evidence that dam operations during the last 10 yr under the preferred alternative of the MLFF have not restored fine-sediment resources or native fish populations in Grand Canyon, both of which are resources of significant importance to the program. Some resources of concern, however, have improved under the MLFF, as shown below and also in the preceding chapters.

What Have We Learned from 10 Years of Adaptive Management?

Adaptive management is an integrated, multidisciplinary approach for confronting uncertainty in natural resources issues. It is adaptive because it acknowledges that managed resources will always change as a result of human intervention, that surprises are inevitable, and that new uncertainties will emerge. Active, experimental learning is the way in which the uncertainty is minimized (Walters and Holling, 1990). Adaptive management acknowledges that policies must satisfy social objectives but also must be continually modified and flexible for adaptation to surprises. Adaptive management, therefore, views policy as hypothesis. That is, most policies are really questions, and management actions become treatments in an experimental sense. Our summary of what is known about the influence of the MLFF on downstream resources examines many facets of the Colorado River ecosystem, especially those resources deemed as most important during the EIS process. Substantial importance is also ascribed to those resources affected by the Endangered Species Act of 1973.

Fish Response

The Grand Canyon population of the federally endangered humpback chub (*Gila cypha*) has declined during the past decade under MLFF operations. Only eight native fish species were historically found in Grand Canyon. Six of these were desert species endemic (not found elsewhere) to the Colorado River ecosystem, making this one of the most unusual fish communities in the world (Mueller and Marsh, 2002). Of the original eight, only four remain in Grand Canyon, namely the humpback chub, the bluehead sucker (*Catostomus discobolus*), the flannelmouth sucker (*Catostomus latipinnis*), and the speckled dace (*Rhinichthys osculus*). Of these four, only the humpback chub is endangered, and its numbers have dropped dramatically in the last decade. At the same time, nonnative fish have increased in both diversity and abundance. The reasons for the decline of native fish are commonly cited to include dramatic changes in the thermal, sediment, and hydrologic regimes of the river because of the construction and operation of numerous dams in the basin, the introduction of nonnative 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, in part because of a lack of early data on population numbers.

Our knowledge about the cause and effect between dam operations and chub decline is incomplete; we do know, however, that the current MLFF operation has not resulted in increased survival and recruitment of humpback chub, despite the prediction of the EIS (table 1). Although there is no basis for claiming that the current operation at Glen Canyon Dam resulted in recent and repeated low recruitment and the continued decline of the humpback chub, it is clear that the restrictions on dam operations since 1991 have not produced the hoped-for restoration and maintenance of this endangered species (see chapter 2, this report). During the MLFF, basin hydrology has varied from drought to wet conditions and then back to drought conditions. Through these conditions, the decline of the humpback chub has continued. This trend leads to questions about whether daily, monthly, or even annual patterns of dam

Table 1. Natural and cultural resources of the Grand Canyon ecosystem and predictions from the Operation of Glen Canyon Dam Final Environmental Impact Statement (EIS) table II-7 (U.S. Department of the Interior, 1995) on how these resources would respond under the modified low fluctuating flow (MLFF) alternative, which is the preferred alternative in the EIS.

[Glen Canyon Dam Adaptive Management Program (GCDAMP) is a federally authorized initiative to ensure that the primary mandate of the Grand Canyon Protection Act of 1992 is met through advances in information and resource management. Resources are ordered in this table as they appear in the EIS. A plus sign (+) indicates that the prediction was correct or exceeded expectations, a minus sign (-) indicates that the prediction was not entirely correct or did not achieve the desired outcome, and plus and minus signs together (+/-) indicate a mixed outcome. Data unavailable are indicated by a question mark (?) and may imply a total absence of data or that the data are not available to the U.S. Geological Survey's Grand Canyon Monitoring and Research Center through the research and monitoring program under the GCDAMP]

Resource	Prediction	Outcome	Comments
Sediment and aquatics			
Fine sediment (sandbars 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 powerplant operations and periodic implementation of experimental high 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 hydroelectric power operations.	-	Sandbars continued to erode, and new sand inputs were not accumulated within the main channel. Experimental high flows were conducted, but the lack of flexibility in the timing and frequency of these controlled floods limited their effectiveness.
Coarse sediment (debris flow impacts from tributaries and their influence on the navigability of rapids and terrestrial sandbars) This resource was not included in table II-7 of the EIS (U.S. Department of the Interior, 1995), but predictions regarding the fate of this material were given on p. 104–105 of the document. It is included in this tabulation for the sake of completeness.	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 sandbars 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 sandbars, has been partially mitigated by occasional experimental high 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 to the duration of the high releases.

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Aquatic food web	"Potential major increase"	+/-	Increases were apparent in Lees Ferry reach but not canyon-wide. Fine-sediment inputs from tributaries below the Lees Ferry reach are most likely the limiting factor in primary productivity.
Native fish	"Potential minor increase"	+/-	Recruitment and population of adult humpback chub decreased; native suckers may be stable or slightly increasing.
Nonnative 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 nonnative fish	"Potential minor increase in warm, stable microhabitats" An increase in warm, stable microhabitats would favor native fish and nonnative warmwater fish.	-	Warmer dam releases because of drought-lowered Lake Powell levels may have increased warm microhabitats, but this situation is not directly related to dam operations.
Trout	"Increased growth potential, stocking-dependent"	-	Rainbow trout numbers have increased in the Lees Ferry reach, but condition factor has declined. Stocking is not required.
Vegetation			
Woody plants	Modest increase Exotic species included (tamarisk, camelthorn (*Alhagi maurorum*)).	+	Woody vegetation has increased, especially arrowweed (*Pluchea sericea*) and nonnative tamarisk, in the riparian zone that was formerly inundated frequently under the no action period (1963–91) of hydropower operations.
Emergent marsh plants	"Same as or less than no action"	+/-	Wet marsh species decreased, and dry marsh species increased, likely because of the reductions of daily inundation and without periodic rejuvenation through floods.

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Wildlife			
Wintering waterfowl	Potential increase	+/-	Trends vary by species and are difficult to distinguish from background variation.
Endangered and other special status species			
Native fish (humpback chub, razorback sucker, flannelmouth sucker)	"Potential minor increase"	+/-	Recruitment and population of adult humpback chub decreased; native suckers may be stable or slightly increasing.
Bald eagle	"Potential increase"	?	Numbers in Arizona have increased overall.
Peregrine falcon	No effect	+	Numbers have been 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, but the flycatcher is 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"	?	Not Addressed by Glen Canyon Dam Adaptive Management Program (GCDAMP).
Recreation			
Angler safety	"Moderate improvement"	?	No long-term monitoring data.
Day rafting	"Major improvement"	?	Pre-EIS study suggests that net willingness-to-pay values were insensitive to flows. More studies are needed.
Whitewater boating safety	"Minor improvement"	?	NPS responsibility—not monitored as part of GCDAMP.

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Whitewater boating camping beaches (average area at normal peak stage)	"Minor increase"	-	Camping areas have been diminished because of vegetation expansion and sandbar erosion, despite the fact that the new operating policy has limited daily peaking release to 25,000 cfs.
Whitewater boating wilderness values	"Moderate to potential to become major increase"	?	Potential decrease and decline in campable areas (see chapter 12).
Economic benefits (not related to hydropower revenue)	Positive	+	Increase to both locally and regionally.
Power			
Annual economic cost (foregone hydroelectric power revenue)	Acceptable costs relative to other alternatives	?	Subsequent studies are not available to fully assess.
Wholesale rate of power	Acceptable costs relative to other alternatives	?	Not monitored as part of GCDAMP. See Western Area Power Administration (WAPA) for data.
Retail rate of power (70% of end users)	"No change to slight decrease"	?	Not monitored as part of GCDAMP. See WAPA for data.
Retail rate of power (23% of end users)	"Slight decrease to moderate increase"	?	Not monitored as part of GCDAMP. See WAPA for data.
Retail rate of power (7% of end users)	Acceptable costs relative to other alternatives	?	Not monitored as part of GCDAMP. See WAPA for data.
Nonuse value	"No data"	+	Substantial nonuse value, $3–$4 billion, has been demonstrated as willingness to pay for flows to protect fish.

Table 2. Operating limits and general likelihood of occurrence under the preferred alternative (U.S. Department of the Interior, 1995) of modified low fluctuating flows (maf = million acre-feet; cfs = cubic feet per second).

	General range of hydrologic conditions for Glen Canyon Dam		
Dam releases under operating rules, as well as constrained by annual hydrology	Dry (minimum of 8.23–10 maf of annual release)	Normal (10–15 maf of annual release)	Wet (15–20 maf of annual release)
Minimum releases 7 a.m.–7 p.m. (cfs)	8,000 (likely only during weekends)	8,000 (unlikely to occur)	8,000 (very unlikely to occur)
Minimum releases 7 p.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 h)	5,000 (possible) 6,000 (possible) 8,000 [2] (possible)	5,000 (unlikely) 6,000 (possible) 8,000 [2] (most likely)	5,000 (unlikely) 6,000 (unlikely) 8,000 [2] (most likely)
Ramp rate (cfs/h)	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 (maf)	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.

operation alone are relevant to native fish recruitment or whether changes in the sediment and thermal regimes of the river imposed by regulation have had the greatest influence on native fishes. Further, the issue of nonnative fishes and their potential to limit recruitment of native fish through predation and competition (although highly suspected by scientists as a significant factor) remains unresolved in Grand Canyon.

Populations of both bluehead and flannelmouth suckers appear to have remained relatively stable under the MLFF operating policy. The reasons for this persistence are also unknown. Conversely, the relatively stable habitat conditions created under the MLFF during protracted drought conditions, coupled with a coarsening of substrate in the river channel (see section below on fine sediment), appear to have greatly favored rainbow trout (Oncorhynchus mykiss), particularly in the Lees Ferry reach, as reflected in their increasing numbers during the last decade.

Sediment Response

Research and monitoring have conclusively demonstrated a net loss of fine sediment from the Colorado River ecosystem under the MLFF. Closure of Glen Canyon Dam eliminated about 84% of the sand that historically entered Grand Canyon (see chapter 1, p. 18, this report). Managing the remaining supply below the dam will apparently require carefully managed experimental high flows that are strategically released immediately following tributary sand inputs. It is not yet clear whether even this strategy will succeed in sustainable restoration of sand resources throughout Grand Canyon (Rubin and others, 2002).

Because physical processes related to hydrology and sediment transport were relatively well studied, a logical question is, “Why did the writers of the EIS predict this outcome incorrectly?” Again, the EIS writers did a commendable job of using the best science available, but three critical monitoring programs for measuring suspended-sediment flux throughout Grand Canyon were discontinued in the early 1970s. This situation, and a lack of analytical or conceptual models (Marzolf and others, 1999), forced the EIS team to evaluate only a limited set of sand-transport data after the dam was built and then work with flawed assumptions rather than with continuous data records of flow and sediment concentration. Clearly, long-term monitoring efforts and good models (see Conceptual Modeling text box, Overview, this report) are essential to the success of adaptive management and accurate predictions.

The EIS assumption that sand would accumulate on the bed of the river over multiple years has been transformed through learning and adaptive management experimentation. Recent 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 may be controversial because they bypass the hydroelectric powerplant, 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 experimental high flows that are used for achieving habitat restoration could reduce the financial impacts and controversy associated with such management actions.

A physical habitat component of ecosystem restoration tied to the EIS strategy for restoration of native fish depended on the outcome of modest improvement in fine-sediment resources. As originally proposed in the EIS, restoration of sand-based, nearshore habitats, termed “backwaters,” has also not been realized (see chapter 1, this report) under the strategy of MLFF and hydrologically triggered experimental high flows. Detailed synthesis studies of sediment inputs and outputs to the system (fine-sediment mass balance), intensive field monitoring, and change detection analyses from remote-sensing data all point to a decrease in fine-sediment resources in Glen, Marble, and Grand Canyons in the time since the EIS was implemented. These changes have resulted in smaller and coarser grained sediment deposits that are associated with a net loss of systemwide sand supply and no evidence of accumulating sand from tributary inputs, even under protracted drought hydrology and constrained hydropower operations.

We also know from research on coarse sediment dynamics that there has been an overall trend for the Grand Canyon reach to experience coarsening of the substrate in the river channel since completion of Glen Canyon Dam. As fine sediment is eroded because of dam operations, gravel and larger material remain. The impact of this “coarsening” of the river substrate has two potential biological implications: first is the creation of preferred habitat for benthic invertebrates, which are an important component of the aquatic ecology of the system, and second is the creation of spawning substrate for the nonnative rainbow trout. Both of these changes move the system farther from predam conditions and potentially benefit nonnative species like trout at the expense of natives.

Loss of sand habitats was documented under the no action period (1963–91), and loss has continued since dam operations were altered to reduce sandbar erosion.

Sand-transport data collected from 1999 through 2004 indicate that whenever the monthly flow regime from the dam forces daily peak discharges significantly above 10,000 cfs for extended periods, new and existing sand and finer sediments are being exported relatively quickly (weeks to months), rather than accumulating in the main channel over multiple years.

One alternative test of the MLFF concept for multiyear accumulation of sand supply might be to equalize monthly volumes during droughts in order to further limit daily peaks over such periods. If such a test failed to increase sand supply through accumulation of tributary 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. Meanwhile, release of short-duration, habitat-building flows following significant tributary sand inputs appears to be the most certain option for restoration of sand habitats below the dam.

Water Quality and Climate

The presence and design of Glen Canyon Dam caused major environmental changes to the Colorado River ecosystem, including (1) alterations in the timing and variability of the annual, seasonal, and daily flow patterns of the river; (2) drastic reduction of fine-sediment supply to the reaches of Glen, Marble, and Grand Canyons; and (3) reduced variability in water 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 fine-sediment supply limitation of the downstream ecosystem.

Given the importance of Lake Powell as the major source of water for the Grand Canyon ecosystem below, the lake monitoring program serves as an early warning system for changes in water quality. Although data from Lake Powell indicate that dam operations affect 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. Overall, the water quality of the reservoir appears to be strongly linked to climatic annual to decadal variability governing spring inflow events and to the aging of the reservoir. The reservoir does have the potential to exert substantial impacts on downstream resources, however. For example, the current drought that started in the late 1990s reduced the level and volume of Lake Powell to elevations not seen since the reservoir began filling in the 1960s. The lower storage level of the reservoir has brought warmer surface (epilimnetic) waters to the penstocks, causing higher temperature water to be discharged downstream.

The effects of warmer water on downstream biological resources are currently difficult to predict with certainty and potentially include both positive and negative ecological consequences. Potential consequences include the creation of conditions that support the mainstem spawning of native fish, the invasion and dominance of warmwater fishes from Lake Mead, undesirable alteration of the food base, and unknown effects on the coldwater fishery in the Lees Ferry reach. This “natural” warming of Glen Canyon Dam releases that result from falling reservoir levels provides an important opportunity to test system responses to the possible installation of a temperature control device on the dam.

Current understanding of global climate drivers provides little ability to predict the timing or extent of droughts over much of the Colorado River Basin. The current drought may or may not be a so-called “mega drought” because of the limited duration to date. At the time of this writing we are cautiously optimistic about precipitation and runoff predictions for the basin, but the final outcome will have little to do with dam operations.

Human Use of the River

During the latter part of the 20th century, societal values associated with river regulation began shifting away from a policy focused solely on water supply and energy development to one in which preservation of natural resources was also valued. This shift in values occurred only after river regulation by mainstem dams was well underway on the Colorado River.

River regulation in itself has facilitated the development of an economically significant business associated with whitewater rafting (see chapter 9, this report) by reducing the predam variability in flow extremes of the river and thereby allowing such activities to continue with relative economic safety throughout the year. Recreational use of the river is one of the resources of concern that appears to have benefited most from the stabilizing influence of the MLFF, relative to more variable dam operations. By eliminating very high and very low discharges, the MLFF favors year-round recreational boating and fishing. Although the most comprehensive regional economic study of river-based recreation is now 10 yr old, the figures are impressive: over $46 million (2004 dollars) in nonresident total expenditures and maintenance of 586 jobs, with 438 jobs in commercial rafting alone. Presumably those figures are even higher today.

Camping

Between 1998 and 2003, camping area above the 25,000-cfs stage elevation decreased by 55%, and the average rate of change was 15% per year. The decrease in high-elevation campsite area occurred in Marble Canyon and in Grand Canyon as well as within critical (campsite-limited) and noncritical reaches. Losses are thought to be attributable both to net sediment exports under current dam operations (see chapters 1 and 12, this report) and to encroachment of woody vegetation (see chapter 6, this report). Notably, lower elevation campsite areas increased after 2000, and the total campsite area below the 25,000-cfs stage elevation now exceeds the area available at higher elevations. The rate of decrease in high-elevation campsite area greatly exceeds the decrease in sandbar volume. Vegetation encroachment most likely contributed to the recent loss of high-elevation campsite area.

The exact relationship and interaction among camping areas, vegetation expansion, and dam operations are unknown and provide a challenge for future researchers. For example, increased vegetation in sandbar 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 sandbar stability must also be considered from the perspective that increased vegetation might also limit the potential for wind processes to beneficially blow sand deposits upslope onto cultural sites that are subject to rainfall and runoff erosion.

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

Nonuse Values

Survey efforts tied to the EIS process found that households across the Nation, including those that might never visit Grand Canyon, were willing to pay additional taxes for flows that benefited native fish and trout. Although the amount that people were willing to pay for these benefits was quite reasonable, when aggregated up to the number of households in the population, it produced estimates in the $3 billion to $4 billion (2004 dollars) range (see chapter 9, this report). The public at large is willing to pay to have flows and other management actions that benefit Glen Canyon National Recreation Area, Grand Canyon National Park, and the resources found in both. While there are those who question the utility of nonuse valuation of Grand Canyon resources, these dollar amounts reflect the iconic values that make Grand Canyon National Park famous throughout the world.

Hydroelectric Power Generation

Hydroelectric power and revenue associated with its production and marketing are also highly valued resources of concern to society, and environmental constraints on Glen Canyon Dam operations under the MLFF policy have large, annual economic costs (see chapter 10, this report). The acceptability of those costs has to be interpreted within the context of societal values associated with both electrical energy and environmental conservation objectives. Environmental constraints on dam operations have regional economic impacts on power revenue that is generated to pay back the cost of Glen Canyon Dam and to fund related water-resource and energy development. EIS studies on recreational use and nonuse values, however, suggest that dam operations under the MLFF benefit both local and regional economies through stabilization of flows, despite information that suggests that the ecological objectives of the program (e.g., retention of fine sediment, recovery of the humpback chub) remain unfulfilled.

Because of the constraints imposed on dam operations under the MLFF, the economic value of hydropower that was foregone is unknown. Existing scientific data suggest, however, that the policy, no matter how costly, has not resulted in the level of environmental benefits predicted or desired in the EIS for natural resources below the dam.

An ex post facto cost-benefit analysis of Glen Canyon Dam operations is needed to fully assess the economic value of the MLFF operation versus documented environmental benefits below the dam. Additional experimental designs and the eventual implementation of alternative, longer-term changes in the current operating strategy would benefit from such an assessment.

Water Resources

Water allocation in the Colorado River Basin is governed by the Colorado River Compact of 1922 and subsequent laws and treaties. None of the laws pertaining to water management in the basin were superseded by the Grand Canyon Protection Act of 1992 or the 1996 Record of Decision; therefore, delivery of the volume of water required under these laws, including under the MLFF, has remained unaffected by the Glen Canyon Dam Adaptive Management Program.

Cultural Resources

Under the MLFF operation, sand that is being exported from Grand Canyon is coming not only from new tributary inputs but also from 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 resupplied with new sand sources derived from annual floods during the predam era. Before dam operations were constrained, operations in the no action period (1963–91) were optimized for maximum water storage and power revenue (within the constraints of existing law and policies) rather than for strategically conserving limited sand supplies remaining downstream for restoration of sandbars (and, presumably, long-term preservation of cultural sites). The MLFF operation has not mitigated sand export, and therefore the sand supply remains critically limited. With more sand leaving the ecosystem than being supplied, more and more of these archaeological sites are being exposed to the ravages of erosion. As sites are eroded, artifacts and structures are exposed, making them more susceptible to visitor impacts and destabilization because of the loss of the surrounding sedimentary matrix in which they are buried. Such changes make it difficult, if not impossible, for archaeologists to reconstruct and interpret the historical and cultural information contained within these important settings within Grand Canyon.

In addition to being valued by scientists for the information that the archeological sites provide, the sites are also valued by many Native American people who have traditional affiliations with these sites and the Grand Canyon area in general. Other resources along the Colorado River that are also valued by the tribes of the region include traditionally used plants, minerals, water sources, and significant landscape features. The effects of the MLFF on these tribally valued resources remain uncertain; the Native Americans engaged in the Glen Canyon Dam Adaptive Management Program would like to see more emphasis placed on monitoring the effects on these resources in the future.

Vegetation in the River Corridor

Glen Canyon Dam operations under the MLFF have stabilized flow conditions that were in effect before the EIS in Grand Canyon and that had significant impacts on riparian vegetation. The EIS predicted a modest increase in woody vegetation (table 1), and that prediction has proven 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, which is also largely correct. Since implementation of the MLFF, there has been a decrease in wet marsh vegetation and an increase in dry marsh vegetation.

The stability of flows has 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 recreational users (see chapter 12, this report). Furthermore, the increase is partially attributable to expansion of nonnative tamarisk (*Tamarix ramosissima*) and arrowweed into the riparian zone. In the terrestrial realm, future research should focus on identifying the responses of wildlife to this fundamental change in habitat structure, striving to understand the relationship between riparian vegetation and insects as related to the food web of the river, and examining the effects of human-mediated removal of nonnative vegetation versus natural disturbance. Understanding the complex interface between dam operations and overlapping elements of both the terrestrial and aquatic parts of the river ecosystem provides even greater challenges.

Integrated Ecological Factors

Although linkages between native fish recruitment and backwaters are not well documented and strategies for achieving sandbar habitat restoration are still being investigated, it is clear that physical habitat availability does not reduce or diminish the need by native fish for a sustainable food supply. Dam operations under the MLFF have resulted in steadier flows and greater minimum discharges of clearer water than operations in the no action period, and this situation has probably led to increases in the standing mass of algae and invertebrates (table 1).

A critical future research need is to develop a better understanding of the linkages between the organic matter and invertebrates and the actual prey base of fish, both native and nonnative. A large amount of data has been collected on the food items consumed by nonnative rainbow trout, but only limited data are available for the humpback chub because of the endangered status of this fish. Use of stable-isotope analysis will be critical to assessing the energy sources and trophic pathways that are important to fish. Also, critical tests of the hypothesis that competition between nonnative trout and humpback chub is negatively affecting humpback chub populations are not possible because of inadequate data. Eating the same food items is only the first criterion to establish that competition is negatively impacting a particular species. Further research will be required to determine if this hypothesis is supported by data.

Recent Management Experiments

With respect to native fishes, we have learned that, under the MLFF, focused efforts are still required to understand the importance of the sediment and thermal aspects of physical habitat in the early life history of humpback chub and other species. Focused efforts are also needed to understand the influence of introduced nonnative species on the successful recruitment of humpback chub to the adult life stage. Additional experiments in these areas will require even more commitment to the adaptive management approach by using repeated implementation of both flow and nonflow treatments over an extended period of perhaps 10 or more years coupled with long-term monitoring.

Mechanical removal of nonnative fish, especially rainbow trout, is currently in the third year of a 4-yr 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 (see U.S. Department of the Interior, 2002, for details of the current experimental design). While the adaptive management program has demonstrated that mechanical removal is an effective way to significantly reduce the number of nonnative trout in the removal reach, it has yet to detect the desired increase in the number of spawning-age humpback chub.

In addition to understanding how aquatic ecology, dam operations, and fish populations of the Colorado River ecosystem are interrelated, scientists need to focus future research on the effects of warming discharges of water from Glen Canyon Dam. An experimental temperature control device has been proposed for the dam later in this decade, and substantial questions remain unanswered as to the efficacy of this experimental treatment with respect to both its risk and its cost benefit.

As linkages between the aquatic ecology of the river and its native and nonnative fishes are defined, new efforts for tracking critical elements of water quality will need to evolve to track bioenergetic pathways and fish responses to flow treatments such as temperature control device operations. Also, as more information becomes available about the role of fine sediment in the preservation of cultural sites, aquatic ecology, and fish recruitment, there will need to be a commitment to modeling and monitoring of long-term fluxes of suspended organic and inorganic materials through the river system.

Conclusions and Future Challenges

Research and monitoring conducted by U.S. Geological Survey scientists and their cooperators have conclusively demonstrated a net loss of sediment from the system and have documented the decline of the federally endangered humpback chub during the last decade. At this first milestone, both findings are critical pieces of information to assess conditions and adjust management actions in the spirit of adaptive management. It is important to note that water-delivery requirements continued to be met throughout the decade after the EIS, despite increased costs associated with environmental and experimental regulation of flows.

Although incomplete, a substantial body of knowledge now exists for the Colorado River ecosystem in Grand Canyon. The overarching question is, “What will society do with the knowledge now available to move into the next active phase of the Glen Canyon Dam Adaptive Management Program?” The complexity of the natural system presents enormous challenges for determining how resources and population numbers vary in time and space and underscores the importance of long-term studies to describe patterns and processes. The next critical phase of adaptive management requires strategic action on the part of both managers and scientists.

Along with future action come the continuing challenge and need for greater integration of monitoring and research studies. As the complexity of issues in the Glen Canyon Dam Adaptive Management Program becomes more obvious, so does the need for interdisciplinary, not just multidisciplinary, science. Good examples of recent interdisciplinary science include (1) the interface between fine-sediment studies and cultural resources as the result of research efforts to understand the deposition of wind-carried sediment, (2) water-quality studies related to temperature and fish biology, and (3) the developing link between aquatic ecology studies and fish diets. Continued efforts will be required to integrate knowledge across disciplines and scales and to develop a more robust conceptual model for the Grand Canyon ecosystem.

A continued adaptive management approach below Glen Canyon Dam, one focused on systematic experimentation, is recommended as a more efficient strategy for learning than the approach initially undertaken of monitoring the MLFF operation without comparing it to other flow and nonflow (e.g., mechanical removal of nonnative fish) alternatives. Future experimental treatments (flow or otherwise) must be evaluated within a strategic framework of periodic milestones and with rigorous scientific review so as to effectively identify viable management options for achieving the desired mix of resource responses. Success in this approach relies first and foremost on managers and stakeholders identifying what is desired, as well as determining whether identified objectives are measurable by science and attainable through dam operations.

In the context of an adaptive ecosystem management process, the information identified at this milestone should lead to a dialog between managers and scientists about what other flow or nonflow alternatives might be considered to achieve the desired environmental outcomes.

Because of the uncertainty about the cause and effect of MLFF operations on Grand Canyon resources and the even greater uncertainty about other conservation options, such as mechanical removal or thermal modification, the next steps in the process seem best approached as ongoing management policy experiments in the spirit of adaptive management, punctuated with frequent milestones at which the state of knowledge gained is assessed by all interested parties.

Critical Issues for Further Research

The synthesis of knowledge from over a decade of research and monitoring in Grand Canyon provides an opportunity to identify critical research needs in the Glen Canyon Dam Adaptive Management Program. The purpose of this report is to establish another milestone in our understanding of the state of resources in Grand Canyon; however, we do not attempt herein to provide an exhaustive or prescriptive list of management options. That effort will require another set of processes and products. Instead, we focus on the drivers, or major science questions, that will need to be addressed in the next phase of adaptive management:

- Why is the humpback chub population in Grand Canyon declining? Specifically, what factors or combination of factors are most influential in this downward trend?

- What is the linkage between native and nonnative fish population dynamics and the aquatic and terrestrial food base, and how are these factors related to dam operations?

- Under a potentially continuing drought scenario for the upper basin of the Colorado River, what are the impacts of warmwater discharges on the ecosystem?

- If additional research demonstrates that sediment inputs from tributaries below the dam cannot be manipulated to achieve the desired conservation of sandbars and backwaters with dam operations, is sediment augmentation a viable option?

- What are the specific linkages between dam operations and archaeological site erosion, and what are the options for preserving the significant variety of culturally important resources and the information values associated with nonrenewable heritage resources?

Experimentation and research are needed to determine what role Glen Canyon Dam operations have had in these issues and whether further changes in those operations can benefit key resources.

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