# Active Adaptive Management of the Colorado River Ecosystem Below Glen Canyon Dam, USA: Using Modeling and Experimental Design to Resolve Uncertainty in Large-River Management

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Abstract: An adaptive management program is underway in the Colorado River ecosystem below Glen Canyon Dam in the southwestern United States. The focus of this effort is to identify dam operations and other treatments that can be used to benefit downstream resources. Adaptive management assumes that ecosystem responses to management policies are inherently complex and often unpredictable. Owing to ecosystem complexity, the direction of resource response cannot always be predicted for proposed policies, even when monitoring data and conceptual models are available. To respond to this challenge, the Glen Canyon Dam Adaptive Management Program has embraced experimentation to identify options for restoring sand bar habitats below the dam and protecting endangered native fish in Grand Canyon. In this setting, learning about resource responses to flow and non-flow "experiments" is valuable, but only to the extent that it leads to resource benefits. In the case of sand bar restoration (flow treatments only), learning may come relatively quickly and policy options may be resolved over timescales of a few years, yet sediment objectives may still not be realized. Alternatively, biological responses of endangered fish may lag behind experimental treatments by years (assessment of both flow and non-flow treatments). In such cases, learning may only occur over timescales of decades, while decline of native fish populations continues. If native fish are restored, then the cost of learning through experimentation is justified, but success is not guaranteed. When learning through the experimental approach occurs, transfer of knowledge may also promote positive outcomes in other river management settings where similar objectives are desired. To identify the most effective options for achieving resource benefit through experimental approaches, uncertainties must be constantly evaluated through a process of repeated knowledge assessment and ongoing planning.

Key words: Colorado River; Glen Canyon Dam; Adaptive Ecosystem Management; conceptual modeling; large-scale experimentation; humpback chub

## 1 INTRODUCTION

An adaptive management effort is based on the premise that ecosystem responses to management actions are highly complex and often unpredictable. However, if such uncertainties are actively embraced and actions are undertaken as experiments, then scientific outcomes can provide new information to managers on the range of possibilities for achieving resource conservation objectives. Following basin-wide development of water supply infrastructure (1930s-60s), impacts of Glen Canyon Dam operations on downstream resources of the Colorado River (USA), have been studied by scientists and engineers since the early 1970s (figure 1). Despite this history of investigation, many uncertainties about the relationship between dam operations and river resources remain. In response to the persistent uncertainties, the U.S. Secretary of the Interior directed the Bureau of Reclamation in 1989, to conduct the first-ever retroactive environmental impact statement (EIS) on operations of a large dam. From 1990 to 1995, intense environmental studies focused on the influence of Glen Canyon Dam operations on native, endangered humpback chub (*Gila cypha*), sensitive cultural preservation sites, sandy shoreline habitats and the concept of using artificial floods to restore sand bars (USDOI, 1995; Marzolf et al., 1999). The concept of using controlled, high releases to restore sand bars was initially tested in 1996, and those experimental results prompted sediment scientists to question the basic strategies for sand bar restoration identified in the 1995 final EIS (Rubin et al., 2002). Following the EIS, other hypotheses about the influence of daily fluctuating flows and river temperature on the early life-history success of native and non-native fish have also been critically evaluated by scientists. To support the river management effort, the EIS writing team also promoted the idea that an adaptive ecosystem management approach be implemented as a means of continually evaluating the influence of the new operating policy on downstream resources below the dam. The EIS team also identified large-scale field experimentation as a tool for managers to use.

In 1997, a Federal advisory group comprised of stakeholders with varied interests in the river ecosystem was established to assist the U.S. Department of the Interior with adaptive ecosystem management implementation. Membership in this federal advisory group includes representatives from: six Native American tribes, seven western states, several federal and state agencies, recreational groups and hydropower interests. In 2002, on the basis of reports from scientists that resources were not being improved under the new dam operating rules, the Glen Canyon Dam Adaptive Management workgroup recommended that new, post-EIS experimental studies be implemented to identify better options for achieving conservation objectives for the river ecosystem. The Grand Canyon Monitoring and Research Center (GCMRC) was created in 1995, to assist the managers by providing science information relating to the project.

While new information from the river ecosystem science program has helped scientists and managers identify questionable hypotheses related to sediment conservation, adaptive management has also led to many new hypotheses about biological river responses to dam operations. This is especially true owing to complicating non-flow factors, such as native and non-native fish population dynamics and interactions. Testing of biological hypotheses about native fish is more complex than those centered on sediment conservation. However, the investment in modeling and experimentation required to support river management and restoration may result in multiple returns when new knowledge about the Colorado River ecosystem is well documented and transferred to other river restoration projects.

The objective of this report is to promote information transfer about how strategies for ecosystem science (conceptual modeling and repeated knowledge assessments) and active adaptive management (large-scale experiments) are currently being used below Glen Canyon Dam to support management decision-making in Grand Canyon.

## 2 ROLE OF CONCEPTUAL MODELING

Following the EIS in 1995, conceptual ecosystem modeling for the Colorado River in Grand Canyon was recommended by the GCMRC. This effort was promoted as a means of identifying gaps in understanding about how dam operations related to river ecosystem processes. The idea of using a model to support the adaptive management effort was embraced by stakeholders and scientists, but possibly for differing reasons. From 1998 to 2001, conceptual ecosystem modeling was undertaken to assess the status of knowledge regarding relationships between historical dam operations and various ecosystem resource responses (see Walters et al., 2000).

The objectives for ecosystem modeling were to: 1) clarify key policy options and performance indicators, 2) identify causal linkages between management options and resource indicators and 3) specify clearly why policy predictions based on synthesis of past data might fail by highlighting particular science gaps (help decision makers to “embrace uncertainty”).

The benefits of the conceptual modeling exercise were twofold: 1) it clearly identified that there was a critical need for diagnostic policy experiments and monitoring programs that would provide data to test hypotheses about sand and fish conservation related to the EIS proposed operations and 2) it more clearly identified the potential benefit of embracing experimental design and implementation to achieve the requisite "learning by doing" in an efficient timeframe.

The Grand Canyon modeling approach focused on existing data and theory and was highly successful in identifying where additional emphasis was needed for ongoing monitoring and research (Walters et al., 2000). Some managers perceived that the purpose of the modeling was to develop highly predictive simulations that could substitute for field studies. However, this exercise demonstrated that the main value of attempting to model such a complex ecosystem is to promote discussions about where cause-and-effect uncertainties exist. Once critical gaps in knowledge were identified in the system, discussions then focused on options for implementing monitoring and research to promote knowledge about the ecosystem's response to various policies proposed by managers.

## 3 VALUE OF MONITORING THE STATUS OF SAND BARS AND NATIVE FISH

The conceptual modeling effort was preceded by some limited monitoring that was initiated during the EIS, but additional, focused monitoring was also implemented as a result of the modeling exercise. Between 1996 and 2001, monitoring data for the ecosystem's sand flux and population numbers for endangered humpback chub indicated that those key resources had continued to decline, despite implementation of new operating rules for hydropower operations specified within the final EIS. These trends highlighted the limitations of traditional environment compliance, but also provided an opportunity for adaptive ecosystem approaches.

Early studies of the influence of Glen Canyon Dam operations on downstream sediment and fishery resources in Grand Canyon identified options for restoring and maintaining critical elements of the river ecosystem. A proposal for sand conservation was centered around the strategy of accumulating the limited amounts of sand that continue to enter the river from tributaries below the dam (about 6 percent of the pre-dam supply). By constraining daily peaking-power hydroelectric operations at the dam, managers hoped that further erosion of existing sand bars would be limited and that new sand supplies would accumulate along the bottom of the river channel. Sand bar restoration could then later be achieved through the occasional release of high flows of relative short duration (artificial floods) that would redeposit accumulated sand from the channel bed to higher elevations along the riverbanks.

By 2001, Rubin et al. (2002), reported data and explained reasons why this strategy for sand bar conservation was inherently flawed. Despite constrained daily hydroelectric operations, export of new and existing sand supplies continues, mostly owing to the fine-grained nature of the deposits and limitations on the remaining supply. Dam releases are devoid of sand owing to the fact that all upstream supplies are trapped in Lake Powell (figure 1). In their 2002 report, Rubin et al., proposed new experimental tests for restoring sand bars, such as releasing artificial floods during or immediately after tributary floods that introduce new sand supplies to the river below the dam. The recent history of progress made in the area of sediment research is summarized by Wright et al. (2005), while results of the sediment experiment recommended by scientists in 2002 and conducted in November 2004, are still being analyzed.

With respect to warm-water, native fish of the river ecosystem, managers initially focused their concerns on the coldwater released from the dam after the reservoir was filled in 1980. Another factor thought to limit native fish recruitment in the river were the diurnal fluctuating flows released from the dam in association with peaking power electric generation. Managers hypothesized that colder temperatures limited growth during the early life stages of native fish and that the frequent stage changes in the river associated with power generation contributed to early life mortality of juvenile fish. The strategy for conserving sand bars was hoped to offset these problems to some degree by promoting the restoration of sand bar habitats along the shorelines where river warming would occur in zones of flow stagnation. These habitats are commonly referred to as “backwaters” and are associated with sand bar morphologies created and maintained by recirculating flow within numerous eddies. The eddies are created at hundreds of locations below the dam by debris-flow fans that constrict the river’s flow at the numerous tributary confluences.

Despite new constraints on the daily hydropower production at Glen Canyon Dam in the 1990’s, monitoring and research data indicated that by 2001, the ecosystem’s sand habitats and native fish were both still in decline. Although more information had become available about why the sand conservation strategy was not working (Rubin et al., 2002), there was much less certainty about which of the factors that were thought to limit native fish recruitment were most important. In 2002, managers resolved to more aggressively explore options for restoring physical habitats and promoting recruitment of native fish.

## 4 CRITICAL ROLE OF EXPERIMENTATION

Some resource trends under the new operating policy of the 1990’s, have been opposite to earlier predictions (continued declines in native fishes and sand resources). On the basis of this information it has become clearer that the desired ecosystem conditions for the Colorado River are more complicated and difficult to achieve than managers originally perceived. As decline of critical sediment and fishery resources continued through 2001, managers requested that scientists develop an experimental design that might be used to further reduce uncertainties and identify options for reversing downward resource trends.

Both the conceptual modeling results and intensified monitoring, compelled managers to recommend that additional experiments be conducted to identify options for achieving management goals. In 2002, the U.S. Geological Survey (now, home of the GCMRC) developed a multi-year plan for flow and non-flow science experiments below Glen Canyon Dam aimed at reducing uncertainties about sediment and fisheries management options. The multi-year design was a significant departure from previous single-year tests that limited potential for learning. Some elements of the proposed long-term design were based on results from an earlier, large-scale flow experiment in 1996, that challenged the original management hypotheses related to conservation of sand bar habitats. Other biological elements of the design (such as physical removal of exotic fish species) were new and had not been suggested during the EIS studies. The multi-year experimental treatments recommended in 2002, are currently ongoing for both biological and sediment resources. While results from these efforts are not yet final, there is a need to continue experimental planning for the next phase of research if the primary questions relating to management of the river ecosystem’s downstream resources are to be resolved.

## 5 AN UNCERTAINTY MATRIX TO SUPPORT EXPERIMENTAL PLANNING

In the conceptual modeling phase of the program, two main sub-models emerged as problem areas for prediction: 1) **Sand input, transport, and storage** – where the statistical dynamics of sediment transport and storage had proven to be extremely complex, especially given that predicted outcomes were needed along the edges of the system (beach habitats) and 2) **Food web structure and trophic interactions –** where scientists could generally predict lower trophic level responses fairly well, but the higher trophic level interaction were the ones that were deemed highly unpredictable. This outcome implied a catastrophic divergence of model predictions related to physical habitat restoration with respect to both near-shore, sandy habitats and thermal regimes! Experimental treatments implemented as part of a proposed long-term design since 2002, have provided additional information about both sand and native fish conservation strategies, but results must be carefully evaluated as future science is programmed. Such “milestones” have a significant role in adaptive ecosystem management.

To facilitate experimental planning, a process of knowledge assessment was formally undertaken by both scientists and managers during 2005. Information about flow and non-flow treatments was assessed relative to desired resource outcomes and the results were compiled into several "uncertainty matrices" grouped by resource area. A graphic example of the outcome of this approach is shown in table 1. Once created, the uncertainty matrix helped focus planning discussions between scientists and managers on key areas of the ecosystem where progress has been made through experimental research and monitoring since the EIS. Presumably, areas of the management effort where both the direction of resource response and its magnitude can be predicted with certainty (non-shaded cells of the matrix), represent treatments that require monitoring, but not additional experimentation. Such treatments may be implemented as management actions by decision makers with relatively low risk. The matrix also shows areas where large uncertainties remain (black cells) with respect to proposed management policies. The black cells indicate treatment options for which scientists cannot currently predict the direction or magnitude of resource response. Hence, these cells represent potential areas where future research efforts may need to be focused if cause-and-effect relationships are to be resolved and uncertainties reduced.

The example matrix presented here (table 1), provides managers and scientists with a map of the uncertainties that persist about proposed management options aimed at benefiting fish and physical habitats. Agreement on these areas of uncertainty helps frame the context for discussions about possible experimental options that might be taken to further advance learning about management options. In the area of sediment conservation, the matrix suggests progress in understanding fine-sediment dynamics relative to dam operations and use of artificial floods to restore sand bars (Wright et al., 2005). However, it is still not certain whether there is a flow prescription for dam operations that will both restore eroded sand habitats and sustain them in the future. While additional experiments might still resolve this question, managers must also identify their desired sand resource condition for the ecosystem.

Development of the example uncertainty matrix was relatively straightforward. However, agreement on which experimental actions to implement to resolve the uncertainties around native fish management may not be so easily achieved owing to a variety of non-scientific considerations. One example of such value-based discussions between stakeholders centers around options for managing toward native fish restoration. There are two types of warm water fishes in the post-regulated Colorado River ecosystem: native and exotic. Both may benefit from restoration of more natural flows (more steady flow), with increased temperature and turbidity. Restoration of more natural conditions might favor both exotic and native fishes, but native chub might suffer from enhanced predation as non-natives also possibly benefit from warmer water and expand in both population and range. As managers discuss options, the largest viable population of endangered humpback chub continues to decline in number and could go extinct within twenty years owing to repeated recruitment failures.

While there have been five varying high-flow tests related to the issue of sediment conservation in the past decade, only two adaptive management treatments have been recently tested as policies aimed at restoration of the native fishery: **1) Steady flow regime over summer 2000**, which the conceptual modeling suggested would not likely have much of an impact, and which scientists did not favor, and **2) Focused removal of exotic salmonids from the main channel habitats**, conducted from 2003 to 2005, in the vicinity of the large tributary where humpback chub spawn 122 km below the dam (treatment reaches both upstream and downstream of the confluence with the Little Colorado River, see figure 1).

It is too early to evaluate the influence of exotic, salmonid removal as an experimental treatment, owing to lag effects between reducing the trout populations in the vicinity of native fish spawning and rearing habitats and juvenile native fish recruitment responses. In addition, interactions between native and non-native fishes in the treatment areas are poorly understood with respect to predation and competition for food resources. The biggest surprises recently have come from the single-year experimental treatment that presented the greatest cost, i.e. the Low Summer Steady Flow test of summer 2000. That treatment had a major impact on the Glen Canyon Dam hydropower resource since it reduced energy generating capacity during the high energy demand season and completely eliminated daily peaking power capacity (daily load following). For this cost, the treatment resulted in: 1) development of warm water microhabitat structure all along the main channel below the dam, and 2) more stable shoreline habitats where juvenile native fishes apparently prospered until diurnal flow fluctuations were re-established after the test in September 2000. The return to fluctuating flow releases in September occurred following a 4-day long experimental flood (Habitat Maintenance Flow) that apparently had surprisingly negative impacts on juvenile fish. In 2000, juvenile humpback chubs that were washed from their spawning tributary (Little Colorado River) into the main channel by summer tributary freshets appear to have survived better under the Low Summer Steady Flow, but surviving for a few months does not imply recruitment to the adult population. It is estimated to take a minimum of four years to determine whether recruitment of juveniles has occurred in response to the summer 2000, treatment. Signs of possible success may be showing up in the most recent native fish data and new information must be incorporated into annual planning. New findings might lead scientists to recommend that the next phase of experimental fisheries work include continued exotic fish removal combined with steady flows throughout the fall seasons of several consecutive years.

Evaluation of the status and trends of exotic and native fish populations in Grand Canyon is highly uncertain because of the difficulties of conducting representative catch-per-unit-effort sampling in a large and turbid river with very difficult access, and because of multi-year delays associated with mark-recapture data. Application of stock assessment modeling procedures, originally developed for managing commercial fisheries, has been helpful for estimating population trends from the historical fisheries data, but not sufficient to resolve whether declines in native fish populations have been caused by the increasing abundance of exotic fishes, dam operations, or a combination of the two. Our ability to detect fish population responses to future experimental flows is weak in spite of the lessons learned from stock assessment modeling and expanded monitoring efforts. In contrast, near-term experimental flows proposed for 2002 through 2005, will likely be highly informative for distinguishing among alternate hypotheses about the response of sediment storage to dam operations.

## 6 CONCLUSION

The Colorado River ecosystem between Glen Canyon Dam and upper Lake Mead, Arizona (figure 1), provides a unique opportunity to test various ideas about river management and the use of adaptive management experiments to help resolve scientific uncertainties about best management practices. Beginning in the early 1990’s, a variety of experimental discharge regimes from the dam have been implemented including the well-publicized 1996 controlled flood and the costly 2000, Low Summer Steady Flow experiment (ca. $20-25 million in lost power revenues). The experimental flows and the extensive monitoring, research, and modeling efforts have focused on quantifying the effects of flow on the storage of fine sediment in the Grand Canyon reach of the Colorado River and on the survival and growth of native fish, with an emphasis on the endangered humpback chub. To date, analysis of sediment and flow discharge data from natural hydrologic events and experimental flows has been more helpful in formulating current flow management regimes focused on sediment retention than use of single and multi-dimensional sediment transport models. Inferences from historical analyses have been limited by the resolution of sediment transport data, while inferences from multi-dimensional models have been limited by difficulties in scaling-up site specific results to reaches that are 10’s to 100’s of km long.

After eight years, the adaptive management program below Glen Canyon Dam in Grand Canyon is showing progress, but it is advancing on the basis of serendipitous results rather than on a commitment to a well planned, long-term, experimental design. Apparently, there are two choices for the future: 1) keep trying seemingly intuitive management options and hope for the desired environmental results, or 2) commit to implementing a long-term treatment plan design that offers the greatest likelihood for identifying certainty with respect to cause and effect relative to dam operations or non-flow management alternatives. There are three basic options for a long-term experimental plan: 1) Titration - progressively more expensive options, 2) Reverse Titration - invest heavily in specific flow or non-flow treatments and then back off to see what worked, and 3) Factorial - comparison of treatment combinations using a multi-year, blocked approach. This last option was recommended by the GCMRC in 2002, but the plan was only partially approved and implemented during 2003-2005.

At present, a knowledge assessment process, including development of “uncertainty” matrices, is being conducted within the adaptive management program to evaluate what learning has occurred since the EIS was completed. Through this process, a review of questions generated during the conceptual modeling phase is accomplished and strategies are refined for further reducing uncertainty in key resource areas. It may be that planning/implementation lead times will leave little choice but a titration design to facilitate learning in this management environment. In that case, managers and scientists need to think carefully about how to deal with the confounding problem of “treatment influence” relative to effects of uncontrollable changes, such as low flows and warm water that may be dictated by protracted climate forcing, such as the current ongoing drought. For endangered fish treatments, scientists desperately need to find ways to reduce the lag time from treatment to recruitment response measurement before collapse of the native fishery is irreversible.

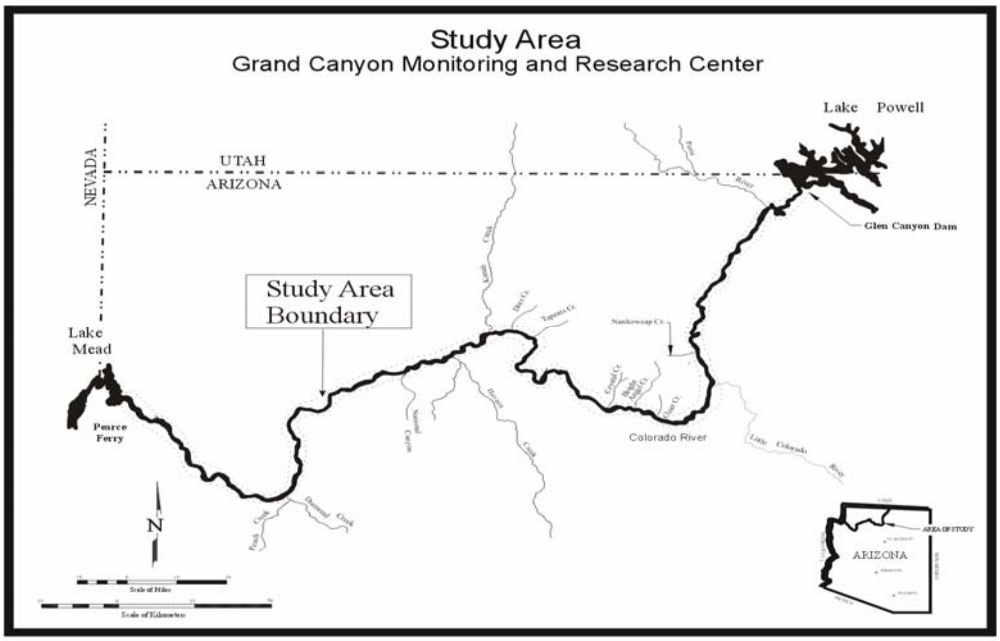


Figure 1: Colorado River Ecosystem, southwestern USA.

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| **Resource Objectives** Restore Sand Habitats & Warm River to Increase Native Fish | Warmer Dam Releases From (Naturally or from A Control Device) | Changing Annual Monthly Release Pattern (Lower Seasonally Adjusted Daily Peaks) | Artificial Floods to Restore Habitats (After Sediment Inputs from Downstream Tributaries) | Increased Daily Fluctuating Flows (Following Peak Energy Demand) | Sustained Low Steady Flow (Below Average Condition) | Sustained High Steady Flow (Above Average Condition) | Physical Removal of Non-Natives, (Cold Water Species Of Fishes) | Physical Removal of Non-Natives, (Warm Water Species Of Fishes) |
|---|---|---|---|---|---|---|---|---|
| Increase Sand in the River | (+) | (+) | (+) | (-) | (+) | (-) | **N/A** | **N/A** |
| Promote Backwater Habitats | (+) | (+) | (+) | (-) | (+) | (-) | **N/A** | **N/A** |
| Support Native Fish Recruitment | (+) | | | | (+) | (-) | | |
| Limit Non-Native Fishes | | | (+) | (+) | | | (+) | |
| Increase Near-shore Temps. | (+) | (+) | (-) | (-) | (+) | (-) | **N/A** | **N/A** |
| More Stable Shorelines | **N/A** | (+) | **N/A** | (-) | (+) | (+) | **N/A** | **N/A** |
| Benefit to Hydropower | (-) | (-) | (-) | (+) | (-) | (-) | **N/A** | **N/A** |

TABLE 1. Example of simplified Uncertainty Matrix for Colorado River Ecosystem in Grand Canyon, USA. The table depicts levels of knowledge about the flow (dam operations) and non-flow treatments with respect to some key river resources of concern, such as hydropower, endangered, native fish and physical habitats. **Notes**: 1) (+), positive response predicted relative to management objective; (o), neutral response; (-), negative response, N/A, not applicable, 2) responses assume dam operations are constrained by fixed monthly volumes, 3) suite of operational elements are contained within column "Increased Daily Fluctuating Flow," such as hourly ramp rate, flow range, peak, minimum flow, for any given monthly volume release, relative to the operational policy implemented in 1996 for the dam. **Shading**: White – scientists can predict the direction and the magnitude of resource response relative to flow or non-flow treatment, Gray – Owing to unresolved uncertainties, scientists can predict the direction, but not the magnitude of response, Black – Uncertainties are so large that a link with dam operations is suspected, but too little is known to make a prediction for resource response direction **or** magnitude of response.