# Assessment of the Estimated Effects of Four Experimental Options on Resources Below Glen Canyon Dam

## Executive Summary

### I. Introduction and Background

The Colorado River corridor through the Grand Canyon is one of the most significant natural areas in the United States. The placement of Glen Canyon Dam on the Colorado River above Grand Canyon National Park and Glen Canyon National Recreation Area altered the river ecosystem. While Glen Canyon Dam provides a number of benefits, including water storage, hydropower, and recreation in Lake Powell, it also causes some significant impacts. Glen Canyon Dam changed the seasonal flows, sediment carrying capacity, and the temperature of the Colorado River. These changes are associated with the decline of native fish, the erosion of beaches and camping areas, the deterioration of culturally significant sites, and the invasion of nonnative vegetation.

In response to public concern about the environmental costs of the dam, the Federal government undertook efforts to reduce impacts to downstream resources by adjusting the operation of Glen Canyon Dam beginning in 1991. An extensive National Environmental Policy Act review process culminated in the signing of the 1996 Record of Decision (ROD) that implemented the modified low fluctuating flow (MLFF) regime as the basis for the operation of Glen Canyon Dam. In selecting the MLFF alternative, the ROD noted that the goal was to "permit recovery and long-term sustainability of downstream resources while limiting hydropower capacity and flexibility only to the extent necessary to achieve recovery and long-term sustainability." In addition to selecting the MLFF operating regime, the ROD also established the Glen Canyon Dam Adaptive Management Program (GCDAMP). Adaptive management seeks to address complex environmental management problems through a dynamic interplay of ecosystem science, management, and policy. The program promotes collaboration through the Adaptive Management Work Group (AMWG), a Federal Advisory Committee composed of 25 stakeholders that makes recommendations to the Secretary of the Interior on dam operations.

The U.S. Geological Survey's Grand Canyon Monitoring and Research Center (GCMRC) has responsibility for the scientific monitoring and research efforts of the GCDAMP, including the preparation of assessments such as this one. In this role, the GCMRC and its cooperators have evaluated the effects of MLFF operations and other experimental activities. *The State of the Colorado River Ecosystem in Grand Canyon* (SCORE; Gloss and others, 2005), prepared by the GCMRC, summarizes the results of numerous studies and synthesizes relevant scientific data collected between 1991 and 2004. Based on the data available, the report found that the MLFF regime had not as of yet resulted in the resource benefits for which it was selected. As a result of these findings, an ad hoc Science Planning Group (SPG) was established in 2005 to develop an effective long-term direction for future dam operations and experimental research activities. Over the course of a year, three experimental options were developed by various GCDAMP participants through the SPG process. In October 2006, a fourth option was added to the list of options under consideration at the request of the Technical Work Group.

This assessment considers four experimental options (table E.1) that were defined primarily by GCDAMP stakeholders. Referred to as Options A, A Variation, B, and C, each option reflects different philosophies and policies related to the conservation and use of Grand Canyon resources, and the role of science in the GCDAMP. As a result of these differences, the primary dam operations advocated by the four options vary considerably. For example, Options A and A Variation provide for wider fluctuating flows throughout the year primarily to benefit hydropower generation. By contrast, Option B proposes to incrementally implement and test steady flows and equalized monthly volumes of flows primarily to protect downstream resource values. Option C includes both steady flows in the late summer/early fall and wider fluctuating flows during other times of the year.

The purpose of this assessment is to provide GCDAMP participants and Department of the Interior (DOI) decision makers with information about how each of the four experimental options is likely to (a) affect downstream biological, physical, and sociocultural resources of the Colorado River ecosystem (Glen Canyon Dam to upper Lake Mead); influence hydropower resources and associated economic benefits; and (b) contribute to the understanding of the relationships among management actions and resource conditions.

### General Methods

The assessment of the possible influence of the four options on downstream resources is made primarily through the use of information reported in the 2005 knowledge assessment final report (KAR). GCMRC scientists relied on the peer-reviewed literature, both sources cited in the KAR and elsewhere, and the range of expert opinions from well-known scientists that were shared during the 2005 workshop that culminated in the KAR. The estimated resource responses to the proposed experimental options are of a generalized nature and made with admission of the numerous uncertainties that were identified during the knowledge assessment workshop.

New models for simulating the effects of downstream water temperature and diurnal stage variation (DSV) have been completed since the KAR was finalized. The results generated by these models were used to inform the analysis presented in following chapters. The temperature models are also being used to simulate the amount of downstream warming under several temperature control device (TCD) design options for Glen Canyon Dam.

Finally, an economic assessment of the four options has also been undertaken independently by Western Area Power Administration.

## II. The Experimental Options

Four experimental options are considered in this assessment: Option A, Option A Variation, Option B, and Option C. All of the experimental options share several common flow and nonflow actions, including:

- Implementation of a temperature control device (TCD) to elevate mainstem water temperatures and promote humpback chub spawning and recruitment;
- Nonnative fish management to reduce predation on and competition with native fishes; and
- Beach/habitat-building flows (BHBF), or controlled floods, under enriched sand supply conditions to conserve sand resources.

**Table E.1** Summary of flow and nonflow components of the four experimental options under consideration by the Glen Canyon Dam Adaptive Management Program. BASE operations (modified low fluctuating flow regime) are provided for comparison.

| | Flow/Nonflow Treatment | BASE operations | Option A | Option A Variation | Option B | Option C |
|---|---|---|---|---|---|---|
| Flow | Increased daily flow fluctuations | No | Yes (increased by 50% to 66% in winter months and by 25% in summer months) | Yes (increased by 25% to 66% in all months except April and May) | No | Yes (increased by 50% to 66% in winter months) |
| Flow | Stable flows | No | No | No | Yes, (tests of 4, 8, and 12 months) | Yes, (September through October) |
| Flow | Beach/habitat-building flows | Possible, but only under hydrologic triggers | Yes, as tests under sediment input triggering | Yes, as tests under sediment input triggering | Yes, as tests under sediment input triggering | Yes, as tests under sediment input triggering |
| Flow | Alternative ramping rates | No | Yes (hourly downramping rate increased 100% in all months) | Yes (hourly downramping rate increased 100% in Apr–Oct and 167% in Nov–Mar ) | No | Yes (hourly downramping rate increased by 100% in Nov–Jul only) |
| Nonflow | Temperature control device | No | Yes | Yes | Yes | Yes, 2 units assumed |
| Nonflow | Control of nonnative coldwater fish | No | Yes, as needed | Yes, as needed | Yes, as needed | Yes |
| Nonflow | Control of nonnative warmwater Fish | No | Yes, as needed, with R&D starting in 2007 | Yes, as needed, with R&D starting in 2007 | Yes, as needed, with R&D starting in 2007 | Yes, with R&D starting 2007 |
| Nonflow | Humpback chub disease/parasite research | No | Yes | Yes | Yes | Yes, with R&D starting 2008 |
| Nonflow | HBC translocation | No | Yes | Yes | No | [1]Yes |
| Nonflow | Humpback chub refuge(s) | No | Yes | Yes | Possibly | [1]Yes |
| Nonflow | HBC population augmentation planning | No | Yes, Planning efforts toward implementation, as needed | Yes, Planning efforts and implementation | No | [1]Yes, planning phase |
| Flow and Nonflow | [2]Mini experiments | No | Yes | Possibly | Yes | [1]Yes |
| Experimental Design | | Not applicable | Reverse Titration | Reverse Titration | Factorial | Forward Titration |

NOTE: 1) For Option C: Ancillary projects not considered part of the main experiment; implementation decision includes consideration of confounding the main experiment. 2) Mini experiments are short-term field experiments that do not confound main experimental treatment effects. For Option C: These experiments are considered undefined concepts and would be incorporated if defined and not in conflict with the main experiment.

The greatest difference between the experimental options being considered and the current operating regime is the triggering criteria for beach/habitat-building flows. Under current operations, a BHBF can only occur in years when there is an expectation of having a very full reservoir. The current trigger allows a BHBF if the January forecast for the April through July unregulated spring runoff into Lake Powell exceeds 13 million acre-feet (MAF) (about 140% of normal) when the January 1 storage is 21.5 MAF, or if any later monthly forecast for spring runoff into Lake Powell would require a powerplant monthly release greater than 1.5 MAF. However, under the four experimental options, BHBFs could occur under a new sediment-based trigger. A BHBF would be triggered with an input of 1.0 to 1.5 million metric tons of sand depending on how much sand is derived from the Paria River.

## Nonflow Components

All four experimental options include nonflow components in addition to changing the operation of Glen Canyon Dam. Many of the nonflow actions relate to the management and conservation of the Grand Canyon population of humpback chub (*Gila cypha*), a federally listed endangered native fish species.

**Temperature Control Device:** A Glen Canyon Dam temperature control device, or selective withdrawal device, would provide dam operators with the ability to draw water from different depths of the reservoir, including warmer water from near the surface of the reservoir. The Bureau of Reclamation proposes to modify two of the eight penstocks on Glen Canyon Dam, test the effects of selective withdrawal, then make a determination of whether modification of additional penstocks is warranted.

**Control of Nonnative Coldwater Fish:** This project involves mechanical removal of rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), and other nonnative coldwater fish species using electroshocking or other appropriate technologies. Nonnative fish are thought to compete with native fish for food and prey on young native fish. All four experimental options support continued control of nonnative coldwater fish, as needed.

**Control of Nonnative Warmwater Fish:** Managers and scientists have expressed concern that populations of nonnative fishes adapted to warm water, most of whom are already present in Grand Canyon (e.g., channel catfish, *Ictalurus punctatus;* common carp, *Cyprinus carpio;*, fathead minnow, *Pimephales promelas;*, and plains killifish, *Fundulus zebrinus*), may increase at the expense of native fishes under warmer water conditions. All experimental options support continued research of this threat and implementation of control measures as needed with concomitant monitoring of the native fishes, especially humpback chub.

**Humpback Chub Disease/Parasite Research:** This project includes two phases: (1) development and implementation of a monitoring plan for fish diseases and parasites in the Colorado River and its tributaries, with emphasis on those infecting humpback chub, and (2) investigation of mechanisms for control and suppression of important diseases and parasites.

**Humpback Chub Translocation:** This activity would transplant young-of-year humpback chub from the Little Colorado River to appropriate tributaries within Grand Canyon National Park and adjoining tribal lands to decrease the risk of losing the entire Grand Canyon humpback chub population to a catastrophic event.

**Humpback Chub Refuge(s):** This activity would create an off-river refuge population of humpback chub to provide a safeguard against future catastrophic loss with very low risk to the overall population.

**Humpback Chub Population Augmentation Planning:** This activity proposes to evaluate the efficacy and need for augmenting (stocking) humpback chub in Grand Canyon and developing an appropriate plan.

**Mini Experiments:** Mini experiments are short-term field experiments that are intended to assist in providing answers to science questions related to the uncertainties of implementing an option.

## BASE Operations

Referred to as BASE operations throughout this assessment, current Glen Canyon Dam operations specified by the 1996 Record of Decision (modified low fluctuating flow alternative) provide the basis for relative resource response evaluations for the four experimental options considered.

Under normal BASE operations, the daily range in release rates is no more than 8,000 cfs and the release peak fluctuation generally cannot exceed 25,000 cfs except during periods of high regional runoff or for experimental flows. The hourly rate at which flow changes can be made under current operations is 4,000 cfs/hr for upramp and 1,500 cfs/hr for downramp. Under BASE operations, beach/habitat-building flows might occur, but only under the hydrologic triggering criteria.

## Option A

Option A would increase daily flow fluctuations compared to BASE operations for 5 of 12 months. These increases would be greatest in February with a 66% increase over BASE operations (10,000 vs. 6,000 cfs range), while December and January would increase 50% compared with BASE operations (12,000 vs. 8,000 cfs). There would also be a 25% increase in the flow variations compared with BASE operations in July and August (10,000 vs. 8,000 cfs). The flow variations would remain the same as BASE operations from September through November and from March through June. Compared to BASE operations, the hourly upramp rate would remain unchanged at 4,000 cfs/hr under Option A, but the hourly downramp rate would be increased by 100% in all months of the year to 3,000 cfs/hr instead of 1,500 cfs/hr.

Option A includes a number of other "mini experiments" that would be used to refine operations, which could at minimum include:

1. **Summer Stranding Flows**: A stranding flow intended to suppress trout reproduction below the dam would maintain elevated flows (e.g., 15,000 cfs) for 2 or 3 days, followed by a very sharp drop in flows to a minimum level (i.e., 7,000 cfs). A stranding flow would be considered in the period of June, July, or August.

2. **Ponding Flows**: Ponding flows are those relatively high flows that produce slackwater areas in tributary mouths for the benefit of humpback chub.

3. **Electrical Power Production Experiments**: Power production experiments are short-term flow experiments intended to investigate alternative fluctuating flow parameters that might be compatible with downstream resource objectives.

### Option A Nonflow Components

1. **Temperature Control Device** (two units)

2. **Humpback Chub Augmentation**

3. **Humpback Chub Translocation** with translocation efforts focused on other priority tributaries, such as Bright Angel and Shinumo Creeks, plus other possible side streams that are suitable

4. **Mechanical Removal of Nonnative Fishes**, including both coldwater and warmwater nonnative species, as needed

In terms of experimental design, Option A seeks to implement as many treatments as possible as soon as feasible. Option A incorporates reverse titration, meaning that all treatments are implemented to achieve resource benefit until such time that a positive response in targeted resources is detected. Then, treatments may be systematically removed one at a time under continued monitoring until benefits are observed to diminish (learning by undoing). Although learning through this process may be more complicated, beneficial resource response is posited as a priority above establishing cause-effect science results.

## Option A Variation

Option A Variation is a slightly modified version of Option A (described above). The differences between the two experimental options are confined to the daily and hourly dam operations. Option A Variation would increase daily flow fluctuations compared to BASE operations for 10 of 12 months. These increases would be greatest in February with a 66% increase over BASE operations (10,000 vs. 6,000 cfs range), while December and January would increase 50% compared with BASE operations (12,000 vs. 8,000 cfs). In September through November and in March through June, Option A Variation would increase daily flow fluctuations by 25% compared to BASE operations (8,000 vs. 6,000 cfs). A 25% increase would also occur in July and August (10,000 vs. 8,000 cfs). The release flows would remain unchanged relative to BASE operations only in April through May (6,000 cfs). The hourly upramp rate would remain unchanged at 4,000 cfs/hr under Option A Variation compared to BASE operations. However, the hourly downramp rate would be increased by 100% compared to BASE operations in April through October (3,000 csf/hr compared to 1,500 cfs/hr) and by 167% in November through March (4,000 cfs/hr compared to 1,500 cfs/hr). All other flow-based experiments and nonflow components are the same as Option A.

## Option B

Option B would gradually phase in stable flows on a seasonally adjusted basis. Initially, Option B would implement fluctuating flows under current MLFF operations during periods when monthly release volumes are approximately equalized throughout the year (table E.2). Over time, operations under Option B would evolve progressively to seasonally stable flows. Option B starts by equalizing monthly volumes with MLFF fluctuations (Flow A), then combines steady and constrained fluctuating flows of different durations (Flows B and C) with seasonally adjusted steady flows (Flow D). Flows B, C, and D are replicated twice. For the purposes of the 10-year evaluation, Option B returns to MLFF operations after WY 2013, while results of the experiment are being evaluated.

Under Option B, a BHBF would occur immediately once the sediment input trigger is met. However, a BHBF would not occur if there is a high risk of unacceptable negative impacts to young-of-year humpback chub in the mainstem (the criteria for this determination are currently undefined). Experimentation with limited duration “supply conditioning” fluctuating flows might occur before the BHBF to test whether prescribed fluctuations could more evenly distribute the sediment input and thus conserve a larger proportion of the accumulated sediment. In addition, if a subsequent sediment input trigger is met during the same block of experimental flows, then another BHBF test would immediately occur.

Table E.2 Summary of flows associated with Option B for WY2007 to WY2013.

| Dates | Flow | Monthly volume[1] (KAF) | Discharge (cfs)[2] | BHBF[3] |
|---|---|---|---|---|
| October 2006 to July 2007 | A | 700 | ROD fluctuations (7,500–13,500) | No |
| August 2007 to November 2007 | B | 620 | Steady (10,000) | No |
| December 2007 to July 2008 | C | 720 | Constrained fluctuations (⊘ 4,000 daily) | One or more if triggered |
| August 2008 to November 2008 | B | 620 | Steady (10,000) | No |
| December 2008 to July 2009 | C | 720 | Constrained fluctuations (⊘ 4,000 daily) | One or more if triggered |
| August 2009 to March 2010 | B | 620 | Steady (10,000) | No |
| April 2010 to July 2010 | C | 820 | Constrained fluctuations (⊘ 4,000 daily) | One or more if triggered |
| August 2010 to March 2011 | B | 620 | Steady (10,000) | No |
| April 2011 to July 2011 | C | 820 | Constrained fluctuations (⊘ 4,000 daily) | One or more if triggered |
| August 2011 to March 2012 | D | 620 | Steady (10,000) | No |
| April 2012 | | 1,060 | Steady (14,285) | One if triggered |
| May 2012 | | 800 | Steady (13,300) | No |
| June 2012 | | 790 | Steady (13,160) | No |
| July 2012 to March 2013 | D | 620 | Steady (10,000) | No |
| April 2013 | | 1,060 | Steady (14,285) | One if triggered |
| May 2013 | | 800 | Steady (13,300) | No |
| June 2013 | | 790 | Steady (13,160) | No |
| July 2013 to September 2013 | | 620 | Steady (10,000) | No |

[1]Monthly volume is based on the assumption of an 8.23 MAF release year. If more than 8.23 MAF will be released, then discharge will be adjusted proportionally so that monthly volumes remain approximately equal.
[2] Minor fluctuations are allowed for Automatic Generation Control purposes.
[3] BHBF are 41,000 to 45,000 for 1–3 days depending on research objectives.

## Option B Nonflow Components

1. **Temperature Control Device**: Option B calls for the testing of a TCD with three or four units instead of two as currently proposed.

2. **Nonnative Species Control**: Option B includes the control of warmwater and coldwater nonnative species control, as needed, through WY 2016.

3. **Humpback Chub Translocation**: The translocation of humpback chub to other tributaries and the development and management of an off-site genetic refuge at Willow Beach (and/or other sites) could be considered under Option B pending a risk analysis and an evaluation of the options available to meet the perceived need.

In terms of experimental design, Option B is intended to be a factorial approach with replication of stable and fluctuating flow elements. The approach was chosen to attempt the greatest degree of statistical rigor possible under large-scale field experimental conditions with as few confounding treatments as possible. For experimentation starting in WY 2014, Option B includes a reassessment of the status and trends of resource conditions; a reassessment of the effects of flows, temperature, and nonnative control; and further testing (as needed) of both daily and seasonal flow variability, temperature (using a TCD), BHBFs, and nonnative control in a factorial design.

## Option C

Option C relaxes the MLFF operating criteria in 3 months for daily fluctuations and 9 months for ramping rates. Daily flow fluctuations would be increased from December through February compared to BASE operations, up from 8,000 cfs to 10,000 cfs or 12,000 cfs. The downramp rate would be increased from 1,500 cfs/hr to 3,000 cfs/hr during November through July. At a minimum, stable flows (up to 2,000 cfs daily fluctuations) would occur during September and October of each year.

Option C would be implemented in three 5-year segments with the final year of each segment being used to evaluate, report, and determine whether to proceed as planned with the next experimental segment. Evaluation includes determination of whether resource triggers have been reached with subsequent expansion or contraction of factors (actions) determined to be impacting key resources.

Option C includes consistent hydrology from WY 2007 through WY 2016 to allow for an assessment of the effects of the TCD, which is scheduled for water year 2012. Option C assumes the number of TCD units to be two and that the device will be operated from May through October at full capacity.

Option C includes a biological trigger for humpback chub to be determined by the GCMRC in coordination with other scientists and the Science Advisors. The trigger is to be based on numbers of humpback chub in the Grand Canyon population and the population trend of humpback chub, such that if the population declines to the trigger or below the trigger, the Bureau of Reclamation would immediately reinitiate consultation with U.S. Fish and Wildlife Service to determine a course of action to reverse the decline. One of the considerations of that consultation would be a determination of whether sufficient evidence exists to justify the expansion of the steady flow period from September and October into August. If the identified trigger is not realized during the first 10 years of the experiment, re-consultation would still occur prior to the initiation of the third segment in 2017 to determine what changes, if any, would be recommended for dam operations or other actions.

### Option C Nonflow Components

Actions described in the humpback chub comprehensive plan will be considered for implementation based on completion of planning, attainment of technology threshold, and prioritization of budget; the potential for confounding of the experimental plan would be considered prior to implementation of each action. Actions deeded likely for implementation include:

1. **Control of Nonnative Coldwater Fish:** Option C includes experimentation to determine relative efficacy of mainstream and tributary control, and evaluation of levels of control.

2. **Temperature Control Device:** Option C assumes the number of units to be two and that the device will be operated from May through October at full capacity.

3. **Control of Nonnative Warmwater Fish:** This activity is considered in Option C to be a component of the experimental plan and one for which treatments will be developed; however, it is not sufficiently developed for treatments to be assigned at this time.

4. **Humpback Chub Disease/Parasite Research:** Option C considers this component a research and development activity, which likely will be conducted largely in laboratory settings during the first phase. Following the first 5-year phase of research and development, this activity could move to a field phase with well-defined treatments.

Option C defines several experimental activities as ancillary projects, meaning that the individual activity is not a treatment in the experimental design, but one that would be analyzed for its confounding effect on the main experiment. Ancillary projects include **Humpback Chub Translocation, Humpback Chub Refuge(s), and Humpback Chub Population Augmentation Planning.**

Option C makes use of an experimental approach referred to as a forward titration. New treatments would be added incrementally to improve knowledge of the relationships among treatments and the resources affected by those treatments. For example, steady flows in September and October would be implemented in segment 1, a TCD in segment 2, and an August steady flow trigger in segment 3 under certain conditions. Option C calls for the services of a biostatistician to identify much more specifically how this design, which is not to be found in the statistical literature, would actually be implemented. None of the treatments proposed under Option C are considered "management actions," as defined by TWG and AMWG for the long-term experimental plan, in recognition of the large uncertainty associated with the effects of most actions as identified in the 2005 knowledge assessment report. Option C does not support mini experiments until they are better described and analyzed for their confounding effects on the main experiment.

# III. Effects of Proposed Flow Regimes on Resources

The estimated influences on resources resulting from the proposed flow options were assessed by GCMRC scientists on the basis of information contained in the 2005 knowledge assessment report and peer-reviewed literature. Numerical modeling was used to estimate daily stage variation (DSV) and downstream, main channel water temperature warming. Water temperature modeling for each of the four options assumes that a two-unit TCD is operational in the last 5 years of the evaluation period (2012–16).

## Physical Resources

### Downstream Water Temperature

Modeling indicates that only small differences are expected to result in main channel water temperatures from differences in flow releases among the options. Because the temperature differences are in the same range as the model uncertainty, it cannot be concluded that any of the four options will result in any measurable differences in mainstem water temperatures. In terms of nearshore water temperatures, Option B likely provides the most periods of increased nearshore temperatures because it has many more periods of steady flows than Options A, A Variation, and C. Option C ranks second owing to stable flows in September and October. Option A and Option A Variation rank third and fourth, respectively, and are not expected to result in significant differences in nearshore water temperatures from BASE operations.

### Diurnal Stage Variation

Diurnal stage variation is defined as the difference in stage, or water elevation, between the daily low flow and the daily peak flow. Modeling indicates that compared to BASE operations Option B would result in decreases in stage variation of about 3 ft on average for steady flow months and about 1.5 ft on average during constrained fluctuating months. Option C steady flow months (October through November) would result in similar decreases (~ 3 ft) from BASE operations as indicated for Option B; however, the increased fluctuations called for in winter months for Option C would lead to increased diurnal stage variation of about 2 ft on average compared to BASE operations. Options A and A Variation would lead to similar increased variation in the winter as found for Option C; these options would also cause an approximately 1 ft increased variation in the summer expanded daily range months. These estimates are based on averages over the entire river corridor (from Glen Canyon Dam to Diamond Creek, river miles -15 to 226) and for minimum release hydrology (i.e., 8.23 MAF). For the first 10 miles downstream from the Little Colorado River, the DSV is typically around 1 ft less than this average because of local geometry.

### Fine Sediment

In terms of fine-sediment storage, all four experimental options are considered superior to BASE operations. BHBFs may temporarily (over timescales of months) reduce the subsequent export of sand downstream by coarsening the sand on the surface of the channel bed and lower parts of sandbars. Comparison of the flow regimes indicates that Option B has the greatest likelihood of increasing sandbar volume over the long term because it contains significant periods of steady flows and constrained fluctuations, which will result in the slowest rate of sandbar erosion during periods between BHBFs and the greatest potential to retain tributary inputs leading up to BHBFs. Options A, A Variation, and C are thought to rank substantially behind Option B in their ability to increase sandbar volume over the long term.

There are also substantial differences expected between Options A, A Variation, B, or C in terms of sand export during normal operations (i.e., non-BHBF), particularly during minimum dam release years (i.e., 8.23 MAF). Because stable flows transport less sand than fluctuating flows, Option B will transport less sand than Option C, and Option C will transport less sand than Options A or A Variation. Existing data indicate that the fluctuating and stable flows proposed in Option B tend to accumulate tributary sand in the mainstem, while the winter and summer fluctuations of Options A, A Variation, and C tend to be net erosional. It is not yet possible to assign probabilities for increasing sandbar area and volume to each option. Because under wet hydrologic conditions, the sand budget for Marble and Grand Canyons is predicted to be negative for all four options, the details of the hydrographs may be less important, except that deposition at higher elevations during frequent BHBFs may offset erosion occurring during the rest of the year.

## Biological Resources

The available literature definitively concludes that cold water is limiting to primary and invertebrate productivity, native fish reproduction, and native fish swimming ability. Current temperatures of water released from Glen Canyon Dam are below optimum not only for native fishes but also for the population of introduced rainbow trout. Warming dam release water temperatures would be expected to increase the growth and survival of aquatic organisms, including native and nonnative fishes. None of the four flow options results in measurably warmer mainstem temperatures. As a result, the installation and operation of a temperature control device, continued natural warming of dam releases because of drought, or both will be necessary if natural resource managers expect to realize any benefits to aquatic organisms from increased water temperatures.

A number of large-scale experimental treatments have been implemented in Grand Canyon since 2000. Ecosystems generally take months to years to completely respond to such experiments and so the impacts of these treatments on the Colorado River ecosystem are still being assessed. During this time period the population size of the nonnative New Zealand mudsnail (*Potamopyrgus antipodarum*) has increased dramatically, further confounding analysis.

## Aquatic Food Base and Fish

Reduced DSV can be expected to increase habitat stability, which allows for more permanently wetted area that can support algae and invertebrates. Option B proposes the most constrained flow fluctuations and, therefore, could be expected to increase habitat stability more than Options A, A Variation, or C. Because there is reduced productivity in the winter, increased flow fluctuations would not be expected to have much measurable effect on the aquatic food base at this time of year. Of the aquatic organisms evaluated, rainbow trout would be most likely to suffer from the increased winter fluctuations proposed in Options A, A Variation, and C because of habitat destabilization, which can disrupt reproductive activities.

Increased mainstem water temperatures would likely have a positive impact on the spawning and rearing of young native fishes, but the most important factor or factors limiting the overall humpback chub population have not been definitively determined. The primary effects of increased flow variations are expected to be the physical displacement of fish and habitat instability. The larvae and young-of-year of both native and nonnative fish species are most susceptible to flow displacement because of their poorly developed swimming ability. Increased flow variability is expected to reduce spawning success for the Glen Canyon rainbow trout population, especially in terms of the deposition, development, and hatching of eggs, because the stationary redds (nests) and eggs are susceptible to displacement and desiccation. The amount of flow fluctuation proposed varies by option, with the most fluctuation proposed by Option A Variation, then Option A, followed by Option C, with Option B proposing the least amount of flow variability.

### Terrestrial Biological Resources

Terrestrial biological resources evaluated with respect to the flow options being considered include riparian vegetation segregated by surface elevations and two endangered terrestrial animal species, the southwestern willow flycatcher (*Empidonax traillii extimus*) and Kanab ambersnail (*Oxyloma haydeni* ssp. *kanabensis*). Riparian vegetation located below the 25,000 cfs surface elevation will be most directly affected by the flow options being considered. Effects on vegetation in this zone for options A, A Variation, and C may include an expansion of marsh vegetation (cover and diversity) in association with increased winter and summer fluctuations. Option B may maintain marsh vegetation at current levels or marsh area may decline with reduced inundation levels. Under Option B, vegetation would advance shoreward with possible drying of vegetation along the upper edge of the 25,000 cfs surface elevation.

Woody riparian vegetation between 25,000 and 45,000 cfs is expected to become denser under options A, A Variation, and possibly Option C. These same plants may decline under Option B because of reduced inundation levels and possibly reduced ground water availability associated with reduced fluctuations and steady flows.
BHBFs largely affect vegetation up to and slightly above 45,000 cfs surface elevation through scour, burial, and temporary delivery of water. Timing a BHBF after early April may increase salt cedar (*Tamarix ramosissima*) establishment and spread, particularly when associated with Option B. Results associated with an ill-timed BHBF could include channel narrowing because of shoreward expansion of vegetation affected by a BHBF in combination with Option B.

The endangered southwestern willow flycatcher and Kanab ambersnail are most affected by the magnitude and timing of BHBFs. Conservation measures associated with snail habitat, which involve the temporary removal of vegetation during flooding and the subsequent replacement of the vegetation following a high-flow event, appear to be successful at Vaseys Paradise. The potential introduction of New Zealand mudsnails to the spring area during a high flow may be a concern, but how the potential introduction of New Zealand mudsnails may affect ambersnails and their habitat is unknown. Willow flycatcher habitat is most likely affected by late season (June–August) BHBFs, specifically for fledglings that may be shaken from their nest. These potential effects are applicable to BASE operations and all experimental options.

## Recreational and Cultural Resources

Effects of flows on recreation and cultural resources are multidimensional. Studies that evaluate the trade-offs between attributes that are important for maintaining a high-quality recreational experience or maintaining cultural site integrity are very limited, therefore the multidimensional effects of flows on recreation and cultural resources are difficult to quantify. Nonetheless, the available data on flow impacts to single attribute components are fairly robust in some areas, allowing for a general evaluation of the four proposed experimental options in relation to BASE operations. In general, Option B appears to have the most potentially beneficial outcomes for recreation in terms of maintaining campable area, maintaining the types and volumes of flows that are preferred by most recreational boaters and anglers, and increasing safety, navigability, and the overall quality of recreational experience. In terms of cultural resources, Option B also offers the best possibility of restoring and maintaining sandbars at both lower and higher elevations, and it would allow the greatest amount of dry sand to be available during optimal times of year for redistribution to the higher elevation old high water zone within the Colorado River ecosystem where most archaeological sites occur. The one area in which Options A and A Variation may be superior to the others is in terms of reducing potential pathogen loads near campsites.

## Hydropower Resources

Western Area Power Administration provided an evaluation on the economic impacts of the four experimental options. The evaluation concluded that the economic impact apart from the issue of hydraulic head that Option A Variation is consistently above Option A in terms of increased economic value. Both Option A Variation and Option A consistently provided greater economic benefits than those provided by BASE operations in terms of electrical power production. Option C vacillates between positive and negative economic impacts over the 10-year evaluation period. If an August trigger is applied to Option C, then the economic impact of the option is strongly tied to hydrology and hydraulic head when compared to BASE operations. Option B reduces economic benefit significantly compared to the other options in most years. However, Option B returns to modified low fluctuating flows (BASE operations) in 2014–16. For example, under the most-probable hydrological conditions, the total annual economic impact of the four options compared to BASE operations, based on a 10-year average, ranges from a $7.5 million increase in the economic value under Option A Variation to a decrease of $28 million under Option B (2006 dollars).

Each of the four options under consideration includes the testing of BHBFs. The cost of a BHBF varies by option, hydrological condition, and time of the year at which the test takes place. For example, if a BHBF was conducted in the fall of a year with the most-probable hydrological conditions, the cost of the BHBF would range from approximately $3.7 million for Options A and B to $4.3 million for Option C when compared to BASE operations (2006 dollars).

# IV. Effects of Proposed Nonflow Actions on Resources

## Temperature Control Device

Because all four experimental options include the use of a temperature control device (TCD) starting in water year 2012, the effects of the TCD are primarily evaluated with respect to BASE operations, which do not use a TCD. However, because the TCD affects release temperatures for all options, it may also affect the differences between the options since the amount of downstream warming is dependent on the release temperature.

### Physical Resources: Water Temperature

Numerical modeling can be used to evaluate the effects of the TCD by analyzing the last 5 years of the simulation period (i.e., the period when the TCD is in operation). Example model results are shown below.

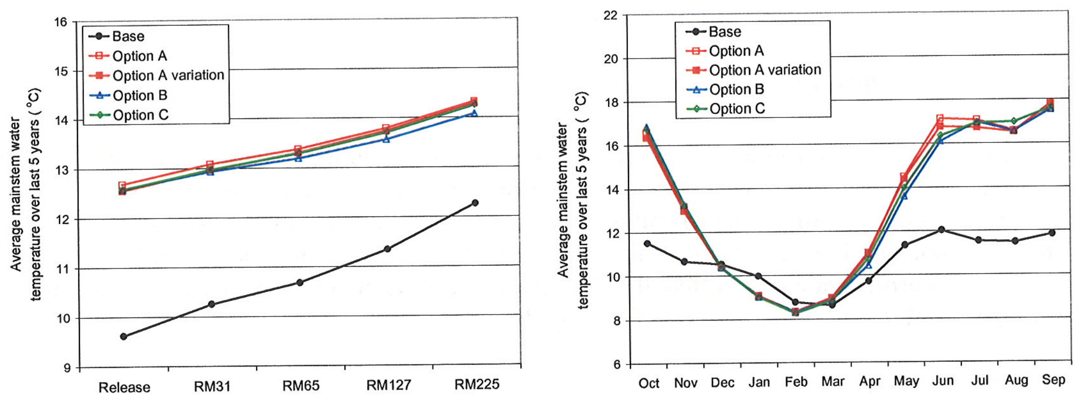


Figure E.1 Average mainstem water temperatures at 5 locations (left) and average monthly temperatures at river mile 65 (right) for the last 5 years of the simulation period (i.e. period with TCD) for most probable hydrologic scenario.

The effects of the TCD are clearly evident in figure E.1 where it is seen that all options have significantly warmer water throughout the system as compared to BASE operations. The warming is greatest in the summer months and typically negligible in the winter.

Because nearshore environments are connected to the mainstem, increased mainstem temperatures are expected to translate to similar increases in nearshore temperatures. Stable flows during months when release temperatures are cooler than air temperatures (i.e. months when downstream warming is expected) are still expected to promote warmer nearshore environments (particularly backwaters). However, because the TCD will tend to bring the mainstem and nearshore temperatures closer to equilibrium with the atmosphere, the impacts of stable flows on nearshore temperatures will tend to be reduced.

A TCD is expected to significantly increase mainstem and nearshore temperatures throughout the system for all options during the spring, summer, and fall. Because release temperatures are increased, the differences between the options tend to be reduced because the differences are driven by downstream warming and downstream warming is less when release temperatures are warmer.

### Biological Resources

The addition of a TCD would increase water temperatures, which would generally benefit native and nonnative aquatic organisms. The primary benefits of increased water temperatures would be increased annual aquatic primary and invertebrate production and increased metabolic rates for native and nonnative fishes that is likely to result in increased growth rates, especially in the presence of increased food (vegetation and invertebrates) availability.

Operation of the TCD may increase the numbers and persistence of Asian tapeworm (*Bothriocephalus acheilognathi*). The proponents of all options being considered recognize that a TCD may benefit both desired and undesired species, in both desired and undesired locations, and so support research and development of methods to control undesired species where and when it is necessary to benefit native fish. The Science Advisors have also concluded that while there are risks involved with the operation of a TCD, the potential benefits to native organisms render the risk acceptable.

The effect of warmer temperature on riparian habitat is largely unknown for vegetation in the Colorado River ecosystem. The zone most likely to be affected by warmer temperatures under all flow options is the zone most proximal to the river (base flow to 25,000 cfs).

### Recreation and Cultural Resources

Increases in water temperature through the implementation of a TCD will likely benefit both anglers and whitewater recreationists. Visitor safety will certainly improve with warmer water temperatures. However, the potential impacts of increased pathogen loads on both fish and humans remain highly uncertain and could potentially negate some of the beneficial effects of warming the water. Uncertainties also exist about how warmer water may effect the trout population; warmwater species could increase and potentially compete with the trout for a limited food supply.

## Nonnative Fish Control

### Biological Resources

The removal of nonnative coldwater fish will reduce the populations of coldwater nonnatives. Similarly, the mechanical removal of warmwater nonnatives would be expected to have negative impacts on their populations. The adult humpback chub population stabilized beginning in about 2000 and has remained stable through 2005 (the most recent year for which data are available), suggesting that mechanical removal focused on coldwater nonnative species has not hurt the humpback chub population. Continued monitoring is needed to fully assess if and how the mechanical removal effort benefits native fish populations.

All of the options being considered include control of nonnative fish populations, as needed. All of the options, therefore, may be expected to have a neutral to positive effect on the native fishes, especially for early life stages.

### Recreation and Cultural Resources

There are localized negative impacts to angling opportunity and quality from removal of trout from tributaries and selected reaches of the river. Additionally, trout removal has been identified by several Native American tribes as a negative impact to traditional cultural property values in the Colorado River ecosystem. Impacts to recreation experience are overall undocumented and therefore unknown, but are likely to be minimal.

## Translocation of Humpback Chub

### Biological Resources

As of 2006, the translocation of humpback chub above Chute Falls in the Little Colorado River has been shown to be successful in that the translocated fish have survived well and have spawned. This suggests that this species may be amenable to physical relocation and that translocation efforts may be expected to add numbers to the overall adult humpback chub population in Grand Canyon. Long-term monitoring is needed to confirm this assumption.

Translocation and any associated reproduction of humpback chub confound the assessment of the impacts of various natural and man-made conditions on humpback chub because population increases or decreases cannot be ascribed to only one factor.

The options vary with regard to the use of translocation. For example. Options A and A Variation call for continued translocation and Option B does not favor translocation. The proponents of Option C only favor translocation if it can be shown to not confound an overall experiment and assessment, which remains to be shown as of October 2006.

## Recreation and Cultural Resources

Depending on where translocations occur, there could be some negative impacts to recreation experience and Native American traditional cultural properties from translocation.

## Humpback Chub Refuge, Propagation, and Genetics Management Planning

The GCDAMP Humpback Chub Ad-hoc Group has identified catastrophic loss as an important threat to the Grand Canyon humpback chub population. This threat has been the primary motivation for the development of plans to establish one or more refuge populations of humpback chub outside of Grand Canyon. A small stock of humpback chub has been established at Willow Beach National Fish Hatchery, Arizona, on the Colorado River below Hoover Dam.

Options A, A Variation, and C support the planning for a refuge, propagation, and augmentation; although, the options do not call for immediate augmentation. Option B proponents do not favor such actions based on the premise that such efforts divert resources from protection and improvement of the wild population and their habitat.

# V. Evaluation of Proposed Experimental Designs

## Options A and A Variation

### Strengths

1. Tests implementation of a suite of actions on overall resource responses, including:
    a. Wider flow fluctuations with associated hydropower generation benefits.
    b. Steeper ramping rates with associated hydropower generation benefits.
    c. Minimum flows to protect food base.
    d. Implementation of a temperature control device (TCD) to elevate mainstem water temperatures and promote humpback chub spawning and recruitment.
    e. Nonnative fish management to reduce predation on and competition with native fishes.
    f. Translocation of humpback chub to other tributaries in the Grand Canyon to provide insurance against population loss.

### Weaknesses

1. The approach presumes, contrary to conclusions contained in the knowledge assessment report, that the actions needed to achieve GCDAMP goals are known.
2. The approach of simultaneously implementing multiple management actions or "mini experiments" will greatly confound the ability to assess the effectiveness of specific management or experimental actions for achieving a desired resource response.
3. Implementing a new flow regime and other actions at this time will confound the assessment of the effects of elevated water temperatures and reduced trout populations on native and nonnative fishes under BASE operations.
4. The option provides for no testing of steady flows to protect/restore downstream resources.
5. There is no basis in the literature for the reverse titration concept. The GCMRC is unaware of how the effects of removing an action could be evaluated statistically.

## Option B

### Strengths

1. Incrementally tests the effects of progressively longer periods of stable flows (habitat stability) and increased water temperatures in combination with other treatments (nonnative fish management, BHBF, etc) on target resources (humpback chub, camping beaches, archeological sites, food base, etc). Option B includes implementation of a TCD.
2. The proposed design provides for testing under two hydrologic scenarios (i.e., replication of the experiment over period of 14 years).
3. Provides a robust test of the effects of steady flows (habitat stability) on target resources (humpback chub, camping beaches, food base, etc) by implementing progressively longer periods of stable flows.

### Weaknesses

1. Natural factors may confound the results of the experiment.
2. Implementing a new flow regime at this time will confound the ongoing assessment of the effects of elevated water temperatures and mechanically reduced trout populations on native and nonnative fishes.
3. The option does not include testing of the effects of wider fluctuating flows on hydropower resources and downstream resources.
4. Length (2 years) and timing of steady flow increments may not be sufficient to evaluate the effectiveness on target resources, particularly if hydrologic conditions vary significantly between years.
5. Specification of how non native fish control and implementation/operation of a TCD will be factored into the experimental design is not provided.

## Option C

### Strengths

1. Tests implementation of a series of treatments to improve knowledge of the relationships among treatments and the resources affected by those actions, including:
   a. September/October steady flows to provide habitat stability and benefit humpback chub.
   b. Possible August steady flow trigger to benefit HBC recruitment.
   c. Wider fluctuations December to February to benefit hydropower.
   d. Relaxed ramping rates in 9 months to benefit hydropower.
   e. BHBFs to conserve sand resources.
   f. Implementation of a TCD to elevate mainstem water temperatures and promote HBC spawning and recruitment.
   g. Nonnative fish management to minimize competition/predation with native fish.
2. Includes a formal review at 5 year interval based on updated SCORE report and knowledge assessment.
3. Limits implementation of treatments and mini experiments that may confound the results of the experiment (e.g., translocation).

### Weaknesses

1. Natural factors may confound the results of the experiments.
2. Implementing a new flow regime at this time will confound the ongoing assessment of the effects of elevated water temperatures and reduced trout populations on native and non native fishes.
3. Specific details on implementation of various treatments using the forward titration design are not provided. The scientific/statistical basis for forward titration concept is unclear.

# VI. Scientific Recommendations

Given the information presented in the first five chapters of this report, it is clear that the selection of an experimental option and an experimental design is not simple. Decision makers must make their choice in the face of scientific uncertainty, and the need to balance scientific learning against potential resource benefit, while also considering cost and legal and policy concerns. Additionally, a great deal rests on this decision: How will Glen Canyon Dam be operated for the next 5 to 20 years? Given the scientific expertise of the Grand Canyon Monitoring and Research Center, and the fact that it has not advanced one of its own experimental option alternatives, the GCMRC provides the following recommendations for consideration in the selection of an experimental option.

## 1. Complete the Current Experiment

The GCMRC recommends that managers continue implementing the modified low fluctuating flow (MLFF) regime for at least another 2–4 years. Such a strategy will provide scientists with the time and data required to fully evaluate the biological responses tied to experimental treatments (mechanical removal of nonnatives) and natural variability (water temperature) imposed on the river ecosystem during 2003 through 2006.

## 2. Evaluating Experiments Relative to Managers' Future Desired Conditions

Members of the Adaptive Management Work Group recently asked: "What is the Best Flow Regime?" Presumably, the best operating regime for Glen Canyon Dam would be one that best meets all of the management objectives for both upstream and downstream resources, but this question cannot be answered by scientists unless managers provide clearly defined resource response conditions that are both measurable and attainable.

## 3. Implement and Scientifically Test a Temperature Control Device

Whatever experimental option is selected, the GCMRC maintains that it should include a science strategy for resolving the issue of temperature as a limiting factor in humpback chub life history. The rationale for such testing is tied to a need to better understand early humpback chub life history in the main channel, as well as potential influences on recreational safety, primary and secondary productivity in the food web, etc.

## 4. Continue Testing of Sand-Enriched BHBFs

Resolving whether or not tributary sand-enriched beach/habitat-building flows achieve sediment conservation should be a high priority. Testing should be continued under recommendations by sediment scientists as opportunities of tributary sand enrichment occur.

## 5. The Role of Hydrologic Variability and Dam Operating Constraints

Variation in natural hydrology of the upper Colorado River Basin and its further expression through physically constrained dam operations may "mask" the influence of flows associated with all of the proposed experimental options being currently considered.

## 6. Attempt to Limit Confounding Variables

To the degree that it is possible, the GCMRC recommends that treatments (flow and nonflow) be isolated from one another to promote learning about causative responses to dam operations and other treatments. The GCMRC recommends taking a disciplined and structured approach to implementing new treatments.

## 7. Approach Stable Flow Tests Logically

General evidence suggests that a more stable flow regime *may* benefit a variety of GCDAMP resources (i.e., humpback chub, rainbow trout, sandbars, food base, etc.); however, further testing is recommended to determine if such perceptions are in fact reality. If increased recruitment of chub is not detected in the next several years, then it might be reasonable to conclude that testing of stable flows is the next logical flow treatment to implement for evaluation.

## 8. Continue Model Development to Support Management Decision Making

Use of modeling can help eliminate false starts and blind paths for experimental evaluation. Flow, temperature, and sediment transport are prime areas where modeling has already provided planning-support benefits and as such should continue to be explored, defined, and supported regardless of which experimental option is recommended next.

The science recommendations outlined above cannot ensure absolute learning about cause-and-effect relationships among dam operations and downstream resource responses. Likewise, such recommendations cannot guarantee that resource benefits will be achieved below Glen Canyon Dam. However, taking an approach that builds on the knowledge gained over the nearly two decades of available monitoring and research data may be the most effective strategy available to the Glen Canyon Dam Adaptive Management Program.