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A DISCUSSION OF THE EVIDENCE FOR PERCEIVED FAILURE OF THE MODIFIED LOW FLUCTUATING FLOW ALTERNATIVE (MLFF) TO BENEFIT MOST ECOLOGICAL RESOURCES BELOW GLEN CANYON DAM, 1991 - 2001

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Introduction

A critical transition from passive to active adaptive management occurred in the Glen Canyon Dam Adaptive Management Program (AMP) in 2003, with the implementation of a series of experimental treatments intended to be the start of a longer-term experimental design (see Walters and Holling 1990 for definitions of AM). Recently, a series of multi attribute utility analysis (MATA) workshops were used to elicit preferences of Glen Canyon Adaptive Management - Technical Working Group (TWG) members for policy options involving flow variation and control of exotic fishes in the Colorado River below Glen Canyon Dam (GCD). The objective of this effort was to better focus planning around long-term experimentation. A surprising result from the analysis was that many TWG members appear to prefer more variable diurnal flow policies than either the initial Low Fluctuating Flow policy (LFF) imposed in August 1991, or eventually the Modified Low Fluctuating Flow (MLFF) policy that has been in place as the Record-of-Decision since 1996 (Figure 1). This is understandable in the case of stakeholders whose interest is primarily to optimize revenue associated with hydropower production at GCD, because the new policy has been quite costly (it has reduced potential value from power production by $50 million/year or more). However, there was also considerable support for more variable diurnal flows from stakeholders concerned about ecological performance measures, particularly recovery of the endangered humpback chub and management of sediment resources. These stakeholders were apparently responding to data and interpretations from scientists indicating that the MLFF policy has not provided benefits to humpback chub and sediment resources as predicted in the Operations of Glen Canyon Dam – Final Environmental Impact Statement (DOI 1995).

Here we review the data presented to the TWG during the MATA process in December 2003, to justify predictions of continued humpback chub decline, relatively poor quality of the Lees Ferry trout fishery (as measured by fish size), and relatively rapid sand loss if MLFF is continued (Rubin et al 2002). One of the justifications for the MLFF policy was apparently an assumption or prediction that the policy would have beneficial ecological effects relative to the more rapid and extreme diurnal flow variations that preceded it (operations termed, *No Action* that occurred from 1966-1990). We show that no such beneficial effects are evident in an ecological sense (except to abundance of exotic trout) and in fact the move to LFF in 1991 and then to MLFF in 1996, is correlated with a relatively sharp decline in humpback chub recruitment. We recognize that in the case of humpback chub, a move to summer-fall steady flows (as favored by some TWG members as one experimental treatment during the MATA workshops) could well produce beneficial effects on chub recruitment. We review evidence about the likely impacts of experimentally moving away from the MLFF policy on other Grand Canyon resources, including sediment, riparian vegetation and cultural resources. We also consider one specific tradeoff in flow policies with possible, but uncertain net benefits to sand conservation – the abandoning of MLFF for expanded fluctuating operations (increased sand export rates) simultaneously accompanied by a relaxation of current constraints (timing and frequency) associated with implementation of Beach/Habitat-Building Flows (BHBF).

Changes in humpback chub recruitment and abundance

The only remaining successfully reproducing population of humpback chub in Grand Canyon appears to be the population that spawns in the Little Colorado River (LCR). Based on recaptures of fish that have been PIT tagged since 1989, some 15-20% of the adult fish in this population die each year owing to natural causes. For a sustainable population, these losses must be replaced through recruitment, and the evidence now available from size composition and growth sampling in the LCR and Colorado River mainstem is that the recruitment now consists mainly of juveniles that have spent most of their pre-adult life (3-4 yrs) in the LCR.

Mark-recapture estimates of population size and trend indicate that recruitment has not replaced natural losses from the LCR population for at least the last decade, and probably much longer (Figure 2). There has been a downward trend averaging around 14% per year in adult abundance since the initiation of intensive monitoring programs in the early 1990s, indicating that recruitment has been only about half of that needed to sustain or stabilize adult population size.

Hoop net catch-per-unit effort (CPUE) indices of juvenile abundance (recruitment measured at age 1), indicate that there was a relatively sudden decline in recruitment sometime around 1990 (Figure 3). The size composition of the population was sampled very intensively in the 1991-1993 period, and from this size composition we can assign probable ages to the fish that were present during that period and we can back-calculate how many recruits must have entered the population during the 1980s, to have produced these early 1990s survivors (Figure 3). This recruitment back-calculation indicates that recruitment was probably declining even before 1990, quite possibly following a period of strong recruitment during the early 1980s.

We cannot say with any confidence that the decline in recruitment that apparently occurred in the early 1990s was caused by the move to MLFF flows; it could equally well have been caused by some unmonitored change in the carrying capacity or mortality conditions in the LCR. However, we can say with confidence that MLFF was not effective at reversing the decline or at providing sufficiently good habitat conditions in the CR mainstem to allow enough recruitment for the population to be sustained. That is, MLFF had either a negative effect or no effect at all, but it certainly did not have the hoped-for measurable beneficial effect on humpback chub required to increase chub population size (one obvious measure of ecosystem restoration identified by managers).

There is a good chance that juveniles dispersing into the mainstem in summer and fall would be able to grow, survive, and return to the LCR for extended rearing if they were to encounter (1) reduced predation by exotic trout owing to mechanical removal treatments, and (2) relatively warm spatial refuges in near-shore locations, as would be created by steady flow conditions in late summer and fall. The Low Summer Steady Flow (LSSF) treatment of 2000, demonstrated that such lateral warming of backwater areas can be quite dramatic. A Summer-Fall Steady Flow (SFSF) experiment would need to maintain conditions for backwater warming from the time of the first summer freshet that disperses juveniles into the main channel (usually mid-to-late summer), until around

November 1 when the equilibrium temperature in standing backwaters decreases (owing to nighttime cooling) to about the same as the main channel temperature. In contrast to this strategy, low, stable flows during the 2000 LSSF treatment were initiated in early June, before the first summer freshets in the LCR and stable flow releases were terminated in early September.

Depending on how much it increases summer and fall temperatures in the main water flow, a temperature control device (TCD) operated at Glen Canyon Dam could considerably enhance the thermal effects of SFSF on backwaters - perhaps even to the degree that steady flows are no longer a requirement for successful recruitment of chub when combined with control of exotic fishes. Juvenile chub are unlikely to exhibit normal first-year growth unless water temperature is at least 18 degrees C in late summer. It is doubtful that such a large impact (4-5 degrees above the temperature now seen in the mainstem near the LCR at that time of year) would be achieved by a TCD alone, if that TCD were also planned to avoid GCD release temperatures high enough to cause negative impacts on the Lees Ferry trout population.

Changes in abundance and size of trout (quality vs. quantity)

Both rainbow and brown trout have increased dramatically under the MLFF policy. Densities of rainbow trout, as evidenced by both electrofishing monitoring data and catch per effort in the Lees Ferry trout fishery, have increased by at least 5-fold (Figures 4-5), while growth and average body size have decreased (Figure 5). Brown trout abundance outside the main population concentration near Bright Angel Creek has increased even more dramatically (Figure 6).

Upstream of Lees Ferry, the rainbow trout population has benefited from two basic effects:

(1) increases in primary production (and presumably insect food production), and
(2) increases in spawning success and juvenile survival.

Using the Grand Canyon Ecosystem Model (GCM), which does detailed predictions of primary production rate using diurnal stage variation and algal biomass development estimates (Walters et al., 2000), we estimate that primary production has increased by at least 30% since 1990. This increase in potential to support trout biomass has been dampened somewhat by shifts in community structure from algae (Cladophora) to macrophytes and from insect production to snail production, and by reduced availability of insects (increased diurnal flow fluctuation apparently promotes drift, i.e. dispersal, of insects, and trout feed mainly on such drifting organisms).

Rainbow trout populations typically show conservation of total biomass, meaning that a given area supports roughly the same total biomass whether that biomass consists of a few large fish or many small ones. This phenomenon creates a severe tradeoff in rainbow trout fisheries between quality and quantity of fish available to anglers, if quality is measured by availability of large fish. Increases in number of recruits to the Lees Ferry population, owing mainly to improved juvenile survival rates over the early life period when juveniles are restricted to using near-shore areas (much more stable environments under MLFF), have led to a dramatic increase in catch per effort measured in numbers of fish per angler day. However, there has been a considerable decrease in the average and maximum sizes of fish caught. It should be noted that the total trout biomass per area likely depends on total flows, with lower total biomass being supported in years of low flow (a more severe size vs. numbers tradeoff in low-flow years) like those seen recently in Glen Canyon. If low flows continue, improvements in fish size under policies aimed at reducing fish density may be considerably less than expected from growth and abundance data gathered during the higher flows of the late 1980s and 1990s.

Experimental food for thought (an example of learning by doing)

Since 2003, an experimental flow treatment has been implemented that consists of increased diurnal flow fluctuations of 5,000-20,000 cfs from January through March (about a factor of 2 increase in the daily stage-change over the maximum change allowed under MLFF), aimed at deliberately reducing rainbow trout recruitment so as to both improve fishing quality (fewer, larger fish) and reduce potential impact of rainbow trout on native fishes downstream. On the basis of preliminary experimental results, approximately 50% of the redds in 2003, in the Lees Ferry reach were excavated after March 31, when flows resumed to normal MLFF operations. The total egg deposition loss owing to Glen Canyon Dam operations in 2003, ranged from 30 to 40 percent in the Lees Ferry reach, with about half of this mortality being a direct consequence of the expanded daily-stage range of fluctuating flows in January through March (Korman et al. 2004). Three flow recommendations for Glen Canyon Dam were made on the basis of results from a 2003 young-of-year (YoY) survey and analysis of otolith microstructure: 1) Fluctuating flows targeting YoY rainbow trout should be implemented from April through July to coincide with the timing of the observed hatch; 2) Summer steady flows very likely improve the growth of YoY rainbow trout; and 3) Sudden reductions in the minimum daily flow have the potential to strand or displace many YoY rainbow trout in the Lees Ferry reach (Korman et al. 2004).

The latter recommendation was based on an almost complete absence of fry from low angle shorelines after the reduction in the minimum flow from 10,000 to 5,000 cfs following the 2003, Labor Day weekend (September's low-volume, MLFF operations). An event-based approach, where flows are increased to approximately 20,000 cfs for 2 days, followed by a reduction to 5,000 cfs for one day, implemented on a monthly basis from May through September, might likely be more effective at reducing recruitment in the Lees Ferry Reach than the January - March experimental fluctuating-flow regime implemented in 2003-2004. Steady flows could be conducted between events to increase water temperatures for native fish downstream and would not have beneficial effects for YoY rainbow trout as their densities would be controlled through the temporary reductions in minimum flow. The effectiveness of the event-based approach on rainbow trout could also be easily monitored, with results available in the same year that it is implemented.

Changes in sand storage and transport (beach-habitat loss)

Recommendation for the MLFF policy in the Operations of Glen Canyon Dam - Final Environmental Impact Statement (DOI 1995), was in part based on the assumption that sufficient tributary-derived sand could be accumulated in lower eddy environments and the bed of the main channel over multi-year periods so as to be available for sand-bar restoration during occasional Beach/Habitat-Building Floods. Recent studies have demonstrated that this premise is false, and that the majority of fine sediment from the Paria River that is delivered during the warm-season runoff (July through October), is transported out of Marble Canyon in a few months to seasons under MLFF operations (Rubin and Topping 2001; Rubin et al. 1998; Topping et al. 2000a; 2000b). This has prompted sediment scientists to recommend testing of three alternate options to the EIS-derived MLFF policy for sand conservation and bar-habitat restoration (Rubin et al. 2002):

- Experimentally test implementation of a controlled flood (BHBF) immediately after significant tributary sediment inputs from the Paria River (and if that is not possible, then),
- Test initiation of low, steady flows immediately after a tributary sediment input until such time that a controlled flood can be initiated, or (if the first two options are not successful),
- Consider future operation of a system to achieve sediment augmentation coupled with controlled floods.

There is currently little debate over whether MLFF operations have failed to produce their intended benefits for sediment resources in Grand Canyon. During discussions at the 2003, MATA workshops, it was hypothesized that relaxation of some constraints on MLFF daily fluctuations might actually increase net conservation of sand, despite contrary predictions made in the EIS. Because the sediment transport-water discharge relationship is non-linear, the notion here was that reduced sediment transport associated with longer periods of low flow under higher daily fluctuations would more than compensate for increased transport during the higher flows. It was also hypothesized that such a benefit might only occur under higher monthly release volumes associated with wetter hydrology when MLFF daily range constraints (no more than 8,000 cfs per day) limit daily flow minimums to relatively high discharges. This sand-transport prediction was recognized to be quite uncertain, as the discharge frequency over a day under a given flow regime would depend on the monthly volume from Glen Canyon Dam, as well as optimized release patterns that would be prescribed for hydropower generation and maximum revenue. In addition, it was recognized that the relative transport rates will depend on the slope of the sediment transport-discharge relationship. Another possibility for enhanced sand-bar conservation under alternative fluctuations was identified to be related to whether or not higher fluctuations could temporarily increase sand volumes stored within recirculating eddies throughout Grand Canyon. An analysis, to quantitatively examine these issues is reported here.

The Western Area Power Administration's (WAPA) Hydro LP model was run under monthly volumes ranging from 400-1,000 thousand acre-feet (TAF) for four flow scenarios (Table 1). The model predicted discharge every hour for a one-week period for each volume and flow regime combination. Three alternate sediment rating curves at the Grand Canyon gage, developed over 3 one-week periods in March, May, and July, 2003, were used to predict the sand concentration as a function of water discharge for each hour

(Table 2). Total sand transport for the week under reach rating curve was then computed as the sum of products between predicted hourly sand concentrations and volumes. It is important to note that the sand transport for a given discharge will depend on the grain size and quantity of sand on the bed (Rubin and Topping 2001) and predictions should not be used to forecast future sand transport rates. We therefore standardized the transport predictions for each flow scenario by the corresponding value under MLFF (i.e. Y = 100 * (x-MLFF)/MLFF), where x is the transport rate under any flow regime for a given GCD volume and MLFF is the corresponding rate under the MLFF flow).

Table 1. Summary of flow regime characteristics for which suspended-sediment transport rates were computed.

Regime	Daily Variation (kcfs)	Total Allowed Range Min/Max (kcfs)	Upramp/Downramp Rate (kcfs/hr)
MLFF (CURRENT POLICY)	5, 6 or 8 (volume dependent)	5/25	4/1.5
5-20 (EXP)	5-20	5/20	5/2.5
5-25 (EXP)	5-25	5/25	5/2.5
STEADY (EXP)	0	Volume dependent	0

Table 2. Sand concentration (mg/l) vs. water discharge (cfs) relationships at the Grand Canyon gage, 2003 (D. Topping, GCMRC, unpublished data).

Period	Daily Range (kcfs)	Equation	R^2
March 6-11, 2003	5-20 (EXP)	Y=9.29e-16*q^4.08	0.97
May 5-11, 2003	7.5-13.5 (MLFF)	Y=9.96*e-22*q^5.49	0.91
July 4-8, 2003	10.5-18.5 (MLFF)	Y=4.80e-20*q^5.07	0.93

The Hydro LP model predicted that maximum flows under each scenario would be maintained for at least 12 hrs of each day during normal weekday operations (Figure 7). Scenarios that allowed for higher maximum flows therefore had higher transport rates than under MLFF, even though the MLFF regime had higher minimum flows (Figure 8). At lower monthly volumes of 400 and 500 TAF, the 5,000 – 20,000 and 5,000 – 25,000 cfs regimes produced similar transport rates, which were 40 and 140 percent higher than MLFF rates, respectively, based on the March 6-12, 2003 rating curve (Figure 8b).

Under higher volumes, sand transport under the 5,000 - 25,000 cfs regime was considerably higher than under the 5,000 - 20,000 cfs regime. Under the range of volumes that were examined, the steady flow alternative had transport rates that were 50 to 80 percent less than those under MLFF; information that was similarly reported in the EIS (DOI 1995). Recent Riverware simulations (operations software used by BuRec for managing storage in the Colorado River basin), predict that 50 percent of the monthly release volumes from Glen Canyon Dam between 2004 and 2010, will be between 600 and 800 thousand acre-feet (Figure 9). Under these volumes, the most conservative sand transport relationship (lowest slope, Table 2) predicted that the 5,000 - 20,000 cfs scenario will increase transport rates by approximately 50 percent to as much as 200 percent, relative to MLFF. The relative differences among the hypothetical fluctuation scenarios were also dependent on the slope of the sand transport relationships (Table 3). The March 2003 rating curve, having the lowest slope, produced the smallest differences between scenarios (Table 2). However, the results shown in Table 3 also suggest that some benefit may be derived from the 5,000 – 20,000 cfs operation (a variation of the originally proposed Low Fluctuating Flow (LFF) alternative in the EIS with relaxed ramping and daily range constraints) over MLFF in higher-volume release months associated with wetter hydrology in the future (as originally hypothesized).

The basic conclusion drawn from the analysis, independent of choice of which rating curve was used; is that daily fluctuations in flow that are reduced in total allowable range, but less constrained than those of MLFF with respect to daily range and ramping rates, will increase the transport rate of sand past the Grand Canyon gage (RM 87) and promote export from the upper third of the ecosystem. This is predicted to be true for most monthly release volumes predicted by Riverware for Glen Canyon Dam under the current, protracted drought impacting the Upper Colorado River basin. It is also likely that this sediment-transport estimate would also apply to the lower two-thirds of the ecosystem as well (below RM 87).

While this analysis has demonstrated that the steadier the flows, the higher the retention of sand below Glen Canyon Dam, it does not necessarily imply that increased daily fluctuations in flows should not be considered as part of long-term experimental treatments by the TWG. This owes to the possibility that such experimental operations might provide both economic benefit, as well as benefit to sand-bar morphologies that support habitat, such as more abundant backwaters following periods of sand-bar restoration that might still be achieved after implementation of options recommended above by Rubin et al. (2002). If an experimental policy that relaxes rules on daily fluctuations is implemented simultaneously with more strategically timed controlled floods, then the overall effect for the sediment resources in Marble and Grand Canyons could turn out to be beneficial overall. It is also possible that strategic implementation of fluctuations after sand-bar restoration floods and prior to periods of warmer, stable releases might provide optimal benefits for promoting chub recruitment if such combined "designer" flows result in increased near-shore nursery habitats. However, in the absence of increased flexibility in the timing of controlled floods, increased daily fluctuations in flow alone will certainly increase the rate at which sand resources in Grand Canyon are eroded in low to medium volume release months.

Table 3. Change in the sand transport rate at the Grand Canyon gage under 3 flow scenarios (see Table 1) relative to the transport rate under MLFF. Relative rates are expressed as a percentage.

Monthly Vol.	5-20 kcfs	5-25 kcfs	Steady
March 6-12, 2003 curve			
400	42	42	-81
500	140	140	-74
600	216	287	-72

700	147	351	-65
800	48	188	-66
900	-1	138	-60
1000	-19	81	-56
May 5-11, 2003 curve			
400	63	63	-89
500	234	234	-84
600	390	562	-83
700	241	719	-76
800	64	323	-78
900	-4	219	-73
1000	-29	120	-69
July 4-8, 2003 curve			
400	57	57	-87
500	203	203	-81
600	330	465	-80
700	210	585	-73
800	59	278	-75
900	-3	193	-70
1000	-26	108	-65

Variability in predicted influence of higher fluctuations on eddy sand bars and related habitats

While there is a high degree of certainty associated with the suspended-sediment transport response below Glen Canyon Dam under MLFF versus experimental fluctuating flows, there is relatively less certainty about short-term sand habitat responses under such proposed alternative operations (see Wiele and Franseen 2001, for more details). Preliminary simulation results for three study sites located within the upper third of the ecosystem suggest that variations in channel morphology and sediment supply will result in highly variable sand-bar responses under alternative fluctuating flows (Figure 10). Of the three sites where the alternative 5,000 – 25,000 cfs fluctuations were modeled, only one site – RM 22 – showed a net gain for sand volume stored in the eddy after four weekly cycles of diurnal operations (Figure 10a). Of the other two sites (both downstream where sand supply was assumed to be relatively greater), one was a clear loser at the end of the experimental simulation (RM 30 shown in Figure 10b), while the most-downstream site showed relatively no change in net volume of sand storage despite small daily changes that occurred around the diurnal release pattern. Interestingly, this third site recently showed a dramatic increase in available backwater habitat following experimental 5,000 – 20,000 cfs fluctuating flow operations of winter 2003-04; an experimental period without a BHBF that followed only moderate sand production from the Paria River in August 2003 (about 30 percent of the average annual sand input).

In conclusion, while the transport estimates described above indicate increased export of sand under the experimental diurnal releases, there is potential for benefit to native fish from maintaining or even creating nursery habitats for YoY chubs in the main channel (e.g. return current channels associated with sand bars) at select sites under limited-duration, but higher fluctuating flows. Any such habitat maintenance to bars derived from expanded fluctuating flows would obviously come at the expense of elevated sand export, but such losses might turn out to be offset by repeated release of controlled floods implemented under relaxed constraints when Paria River sand production is significant. The basic question that remains to be answered at present is whether or not the remaining 6 to 7 percent of the pre-dam sand supply below the dam can be managed with flows alone to restore and maintain sand bars in a sustainable manner, or even to arrest historical patterns of post-dam erosion? The high degree of uncertainty associated with the above question, as well as mixed levels of certainty related to suspended-sediment transport and sand bar responses under diurnal flow patterns suggests that additional field experiments are required before managers can effectively consider all available options for achieving desired outcomes.

Changes in the terrestrial riparian community (vegetation and animals)

As would be expected with flow regulation, the pre-dam flood frequency has been compressed by closure of Glen Canyon Dam in 1963 (Figure 1a). Additionally, the timing of annual high flows has also been delayed from spring to summer, a key finding reported by Topping et al. (2000a; 2000b). Compared with the "No Action" period of 1966-1990, the LFF and MLFF policies between 1991 and 2003, have resulted in further decreases in maximum daily flows as well as increases in minimum daily flows (Figure 1b). These changes have allowed terrestrial vegetation like tamarisk and willow to invade more beach and cobble area, and have probably reduced the recharge rate of groundwater used by plants like mesquite that were naturally restricted to above the natural seasonal high water line. The LSSF experiment of 2000, was associated with formation of a strong cohort of tamarisk within what is normally the MLFF varial zone, and this cohort has been able to survive diurnal flooding for three years now. Most likely a return to higher daily maximum flows would be accompanied by a similar lack of, or very slow, response by the vegetation that has developed within the MLFF varial zone. The LSSF experiment also demonstrated that the timing of planned beach habitat building flows and other flow variations can be critical in establishing or preventing good seeding conditions for species like tamarisk.

Under MLFF, some backwater areas initially developed quite diverse and productive plant and animal communities due to protection from diurnal flooding and scouring. But without natural scouring and renewal events, these areas are undergoing vegetation succession and gradual accumulation of sediments and will likely eventually lose their diverse character.

Changes in cultural resources

Mass storage and transport models are not yet available to accurately predict the net total impact, through combined water and aeolian processes, of altered diurnal flow regimes on amount and distribution of sand available to protect cultural resources. One complicating factor in such modeling is that much of the sand now subject to aeolian movement is from large sand deposits that occurred during major floods well before GCD; such deposits are likely losing mass slowly, independent of managed water flows, and hence would result in exposure of some cultural sites no matter how the water is managed.

Discussion: should MLFF be abandoned?

The MLFF provides an excellent example and warning to practitioners of adaptive management about the difficulties that scientists encounter in trying to determine the ecological impact of a policy change when only before-after monitoring data are available (Walters and Holling 1990). We can develop suspicions about possible unintended side effects of the change (e.g. on native fishes), but it is always possible to explain away any such apparent effects as owing to some other factor that happened to change at the same time. Had at least one alternative flow operating regime, for instance, one with more violent diurnal fluctuations, been implemented for a few years during the 1990s as an alternative experimental treatment for comparison to MLFF, we would be in a much better position today to rule out alternative explanations. So from the standpoint of adaptive management, MLFF should not be abandoned entirely but rather treated as just one of several flow management options to be compared to others within a longer-term experimental plan. The MLFF policy has obviously achieved some stakeholder objectives, particularly those related to interests of the recreational rafting community and trout sport anglers who may care more about catching lots of fish rather than catching bigger fish. Such benefits will certainly lead to pressure from those stakeholders to at least include the policy among future experimental treatments and to seek other ways to mitigate any negative ecological impacts that it may have (e.g. by continuing mechanical removal of exotic predators as well as movement toward more flexibility in strategic implementation of controlled floods to conserve sediment resources).

However, because MLFF does not appear to be a win-win option for all stakeholders, it raises an important ethical issue about who should bear the costs of continuing it exclusively as a management policy. At present, power utilities and their ratepayers are essentially subsidizing, at considerable cost, improvement in the quality of Grand Canyon for some, but not all of its designated recreational uses. It is one thing to impose such cost to protect against the loss of an endangered species, but quite another to do so for the benefit of a limited few stakeholders. Schmidt et al. (1998), suggests that these value-based issues must be addressed and resolved as part of the AMP process to avoid a breakdown in the collaboration among stakeholders that has made adaptive management possible and relatively successful in the Colorado River ecosystem in the first place.

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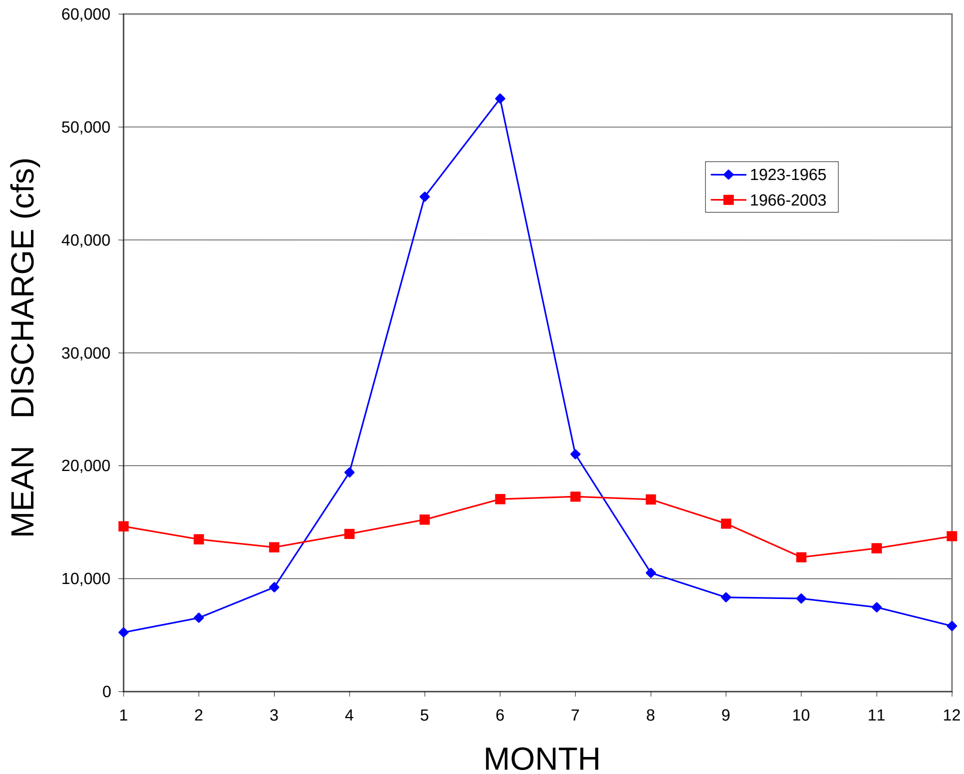
Figure 1. A) Pre-dam versus the post-dam monthly flow at Lees Ferry, B) changes in daily maximum and minimum flow below Glen Canyon Dam since 1948. Low Fluctuating Flow regime (LFF, with maximum daily range of 8,000 cfs and a total fluctuating range of 5,000 – 20,000 cfs) appears after 1990 as the preliminary change in operations, later designated as Modified Low Fluctuating Flow (MLFF, with maximum daily range of 8,000 cfs and a total fluctuating range of 5,000 – 25,000 cfs) in the Record-of-Decision of 1996.

A.



B.

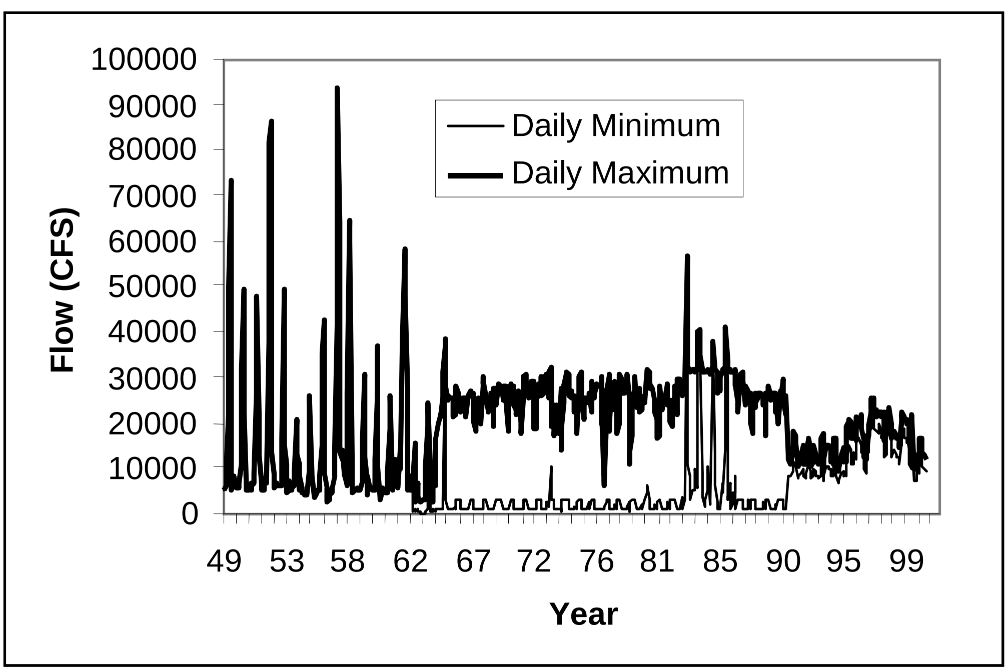


Figure 2. Trends in humpback chub population size in Grand Canyon as evidenced by various estimation procedures based on PIT tagging data.

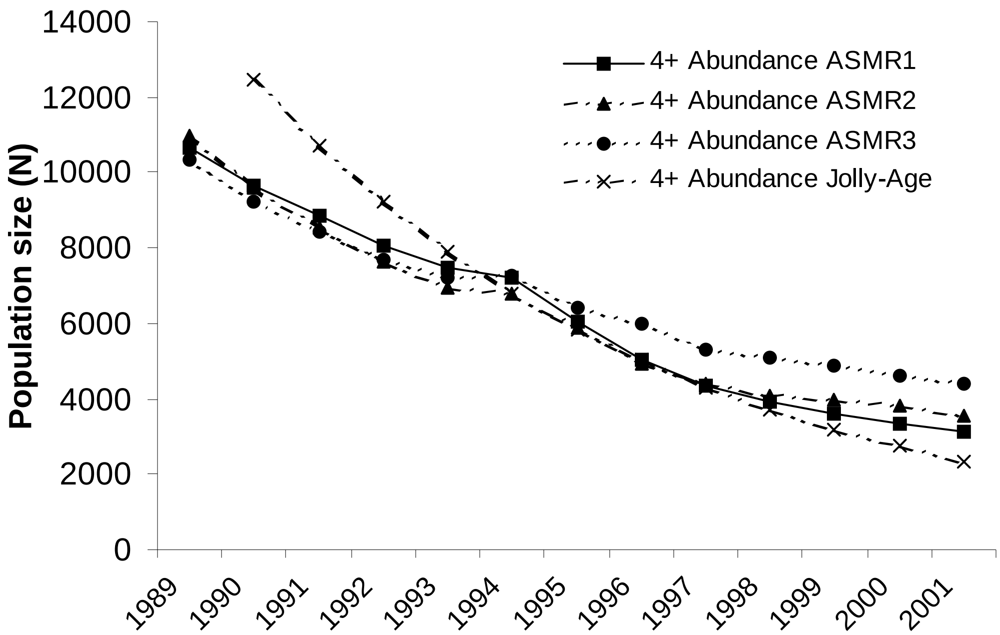
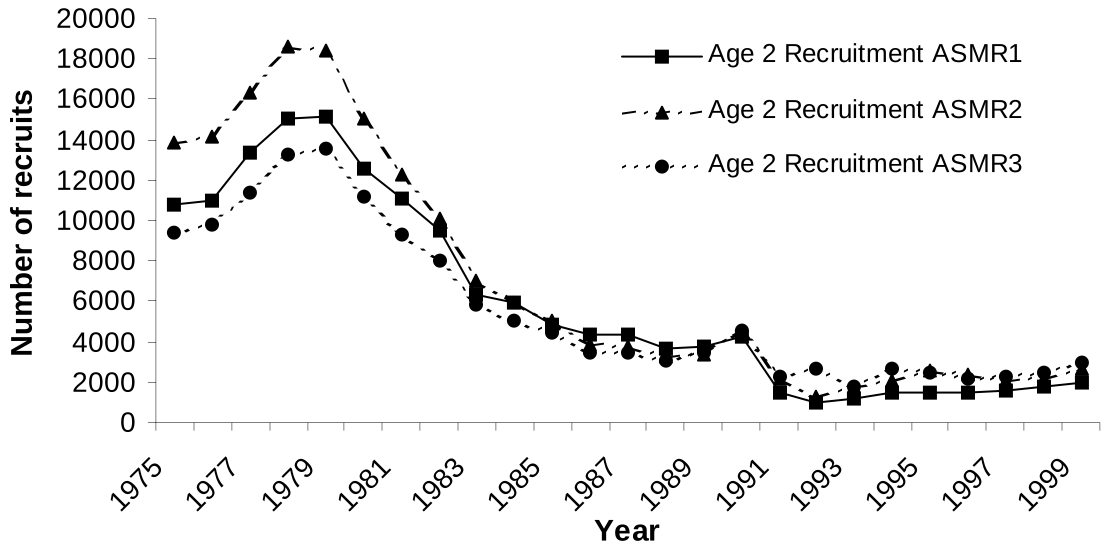


Figure 3. Trends in humpback chub recruitment estimated by A) analysis of PIT tags and from, B) hoop net catch rates near the mouth of the Little Colorado River.

A.



B.

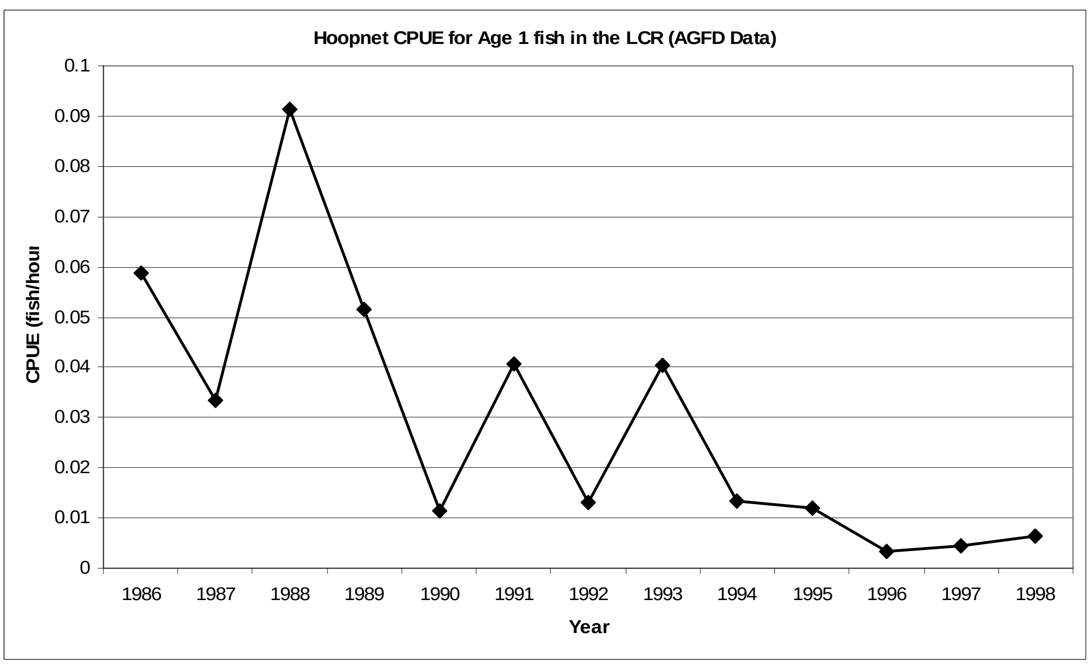


Figure 4. Trends in abundance of rainbow trout in Grand Canyon and Glen Canyon since initiation of MLFF flows**.**

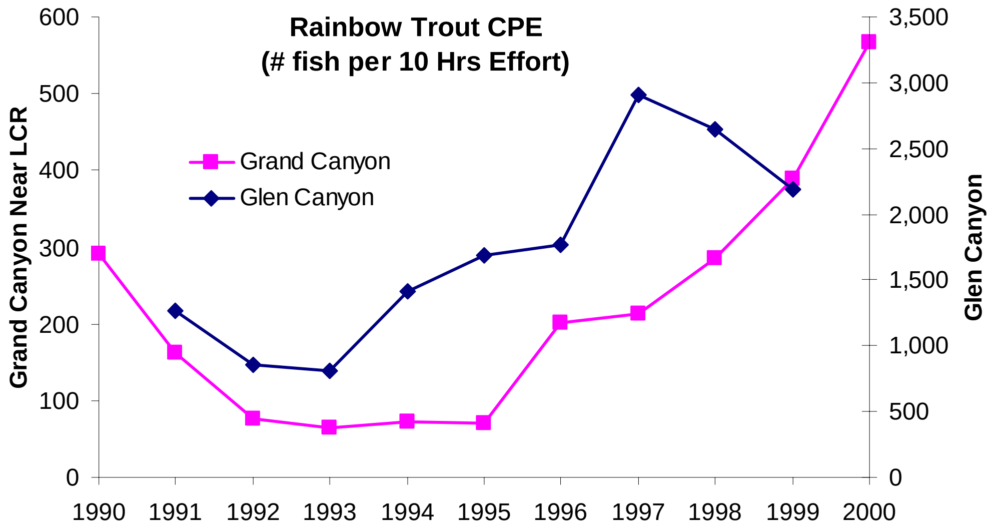


Figure 5. Trends in abundance and mean size of rainbow trout in the Lees Ferry fishery, comparing population model reconstructions to observed trend index data prior to 2000.

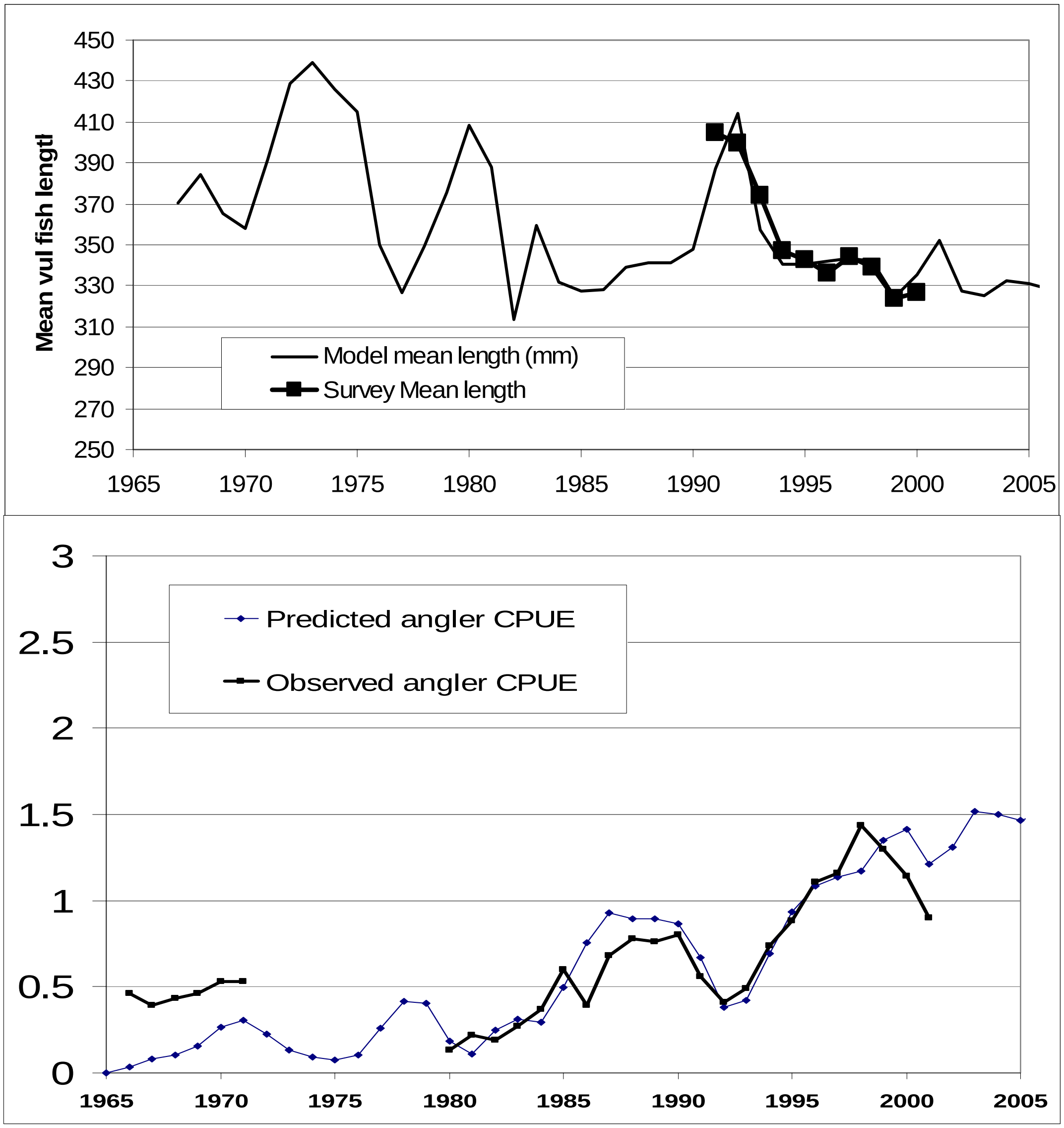


Figure 6. Trends in relative abundance of brown trout (catch per effort from electrofishing monitoring program) in Grand Canyon. Major population concentration is in the region of Bright Angel Creek (spawning area), but dramatic increases have been seen in recent years both upstream and downstream of this concentration. The increase upstream of Bright Angel Creek (river miles RM<80) represents a growing threat to native fishes that spawn in the Little Colorado River (RM 61).

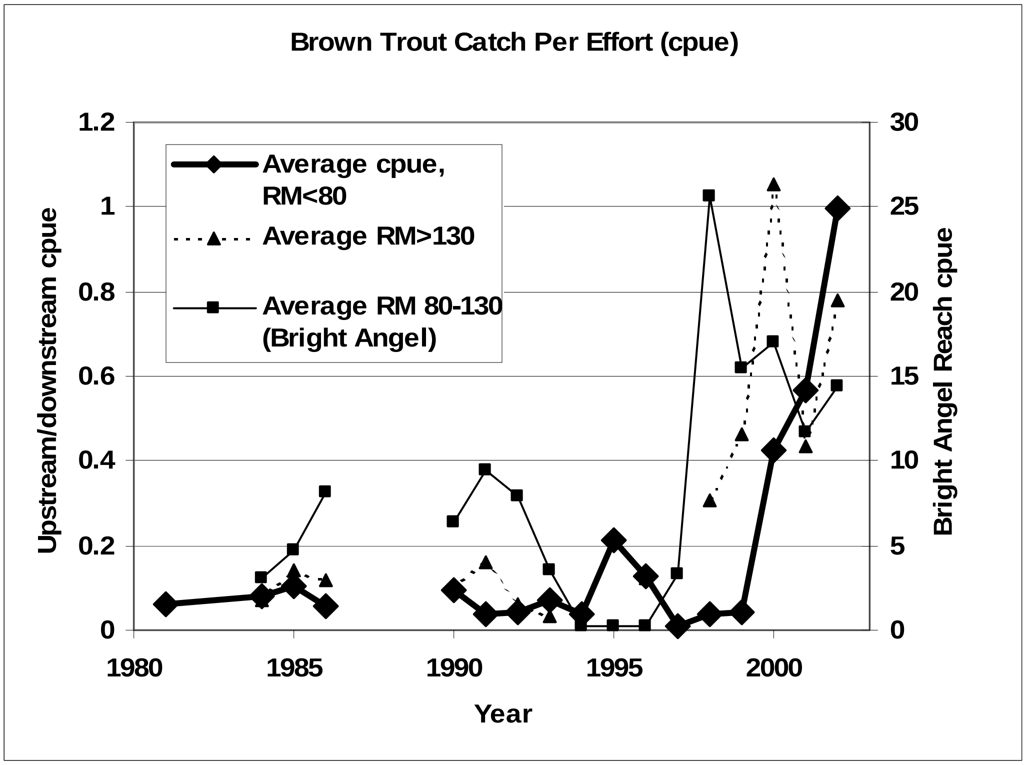


Figure 7. Hourly discharge pattern from Glen Canyon Dam for a one-week period under a release volume of 800 thousand acre-feet for 4 flow scanrios predicted by the WAPA Hydro LP model. See Table 1 for description of scenarios.

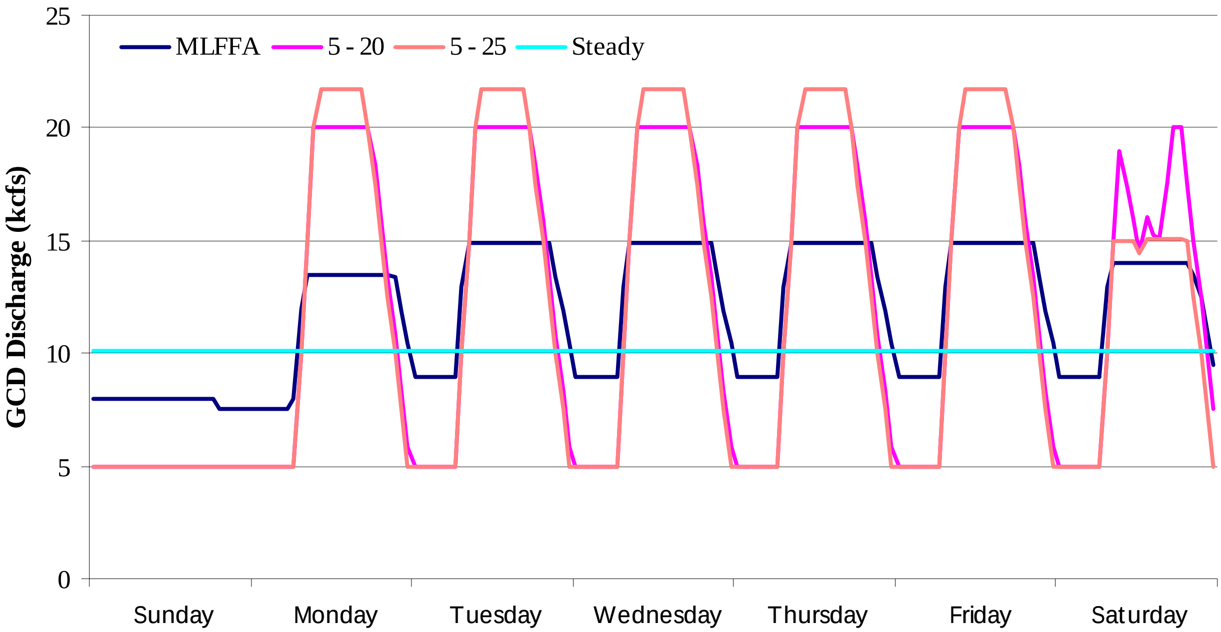
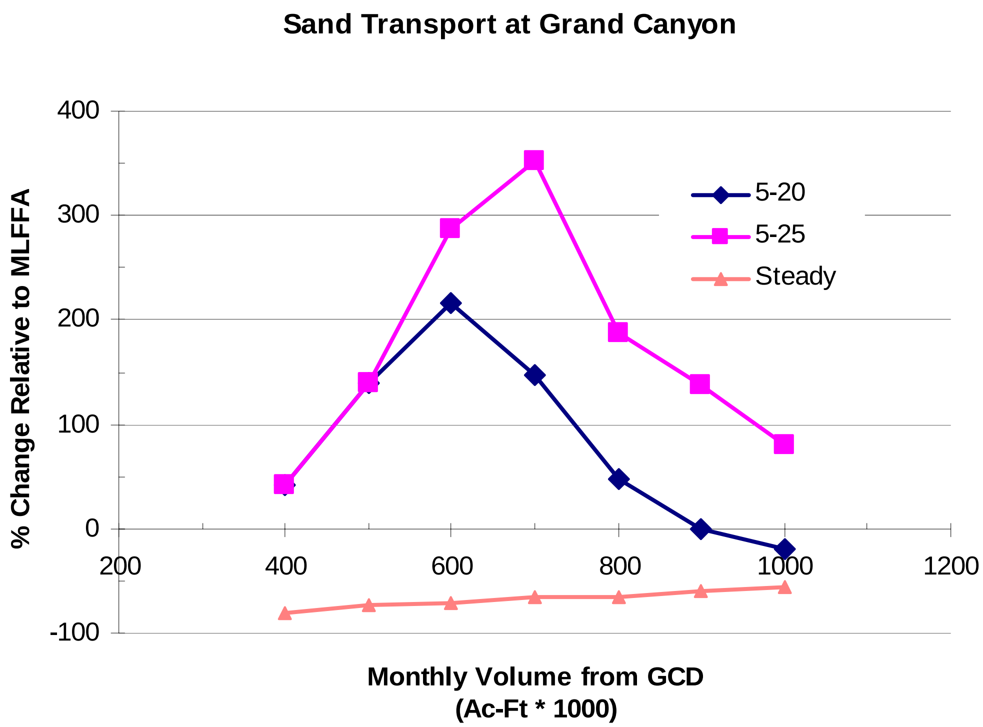


Figure 8. A) shows relative sand transport rates at the Grand Canyon gage (based on March 2003, rating curve shown in B) as a function of the monthly release volume from Glen Canyon Dam under 3 alternate flow scenarios. See Table 1 for a description of scenarios.

A.



B.

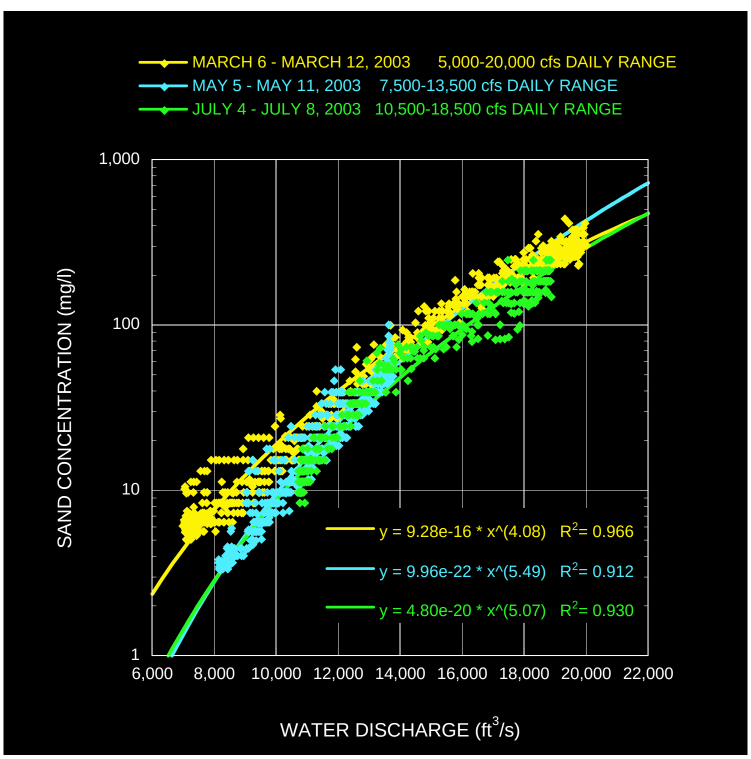


Figure 9. Frequency of monthly volumes released from Glen Canyon Dam predicted by Riveware for the period 2004-2010.

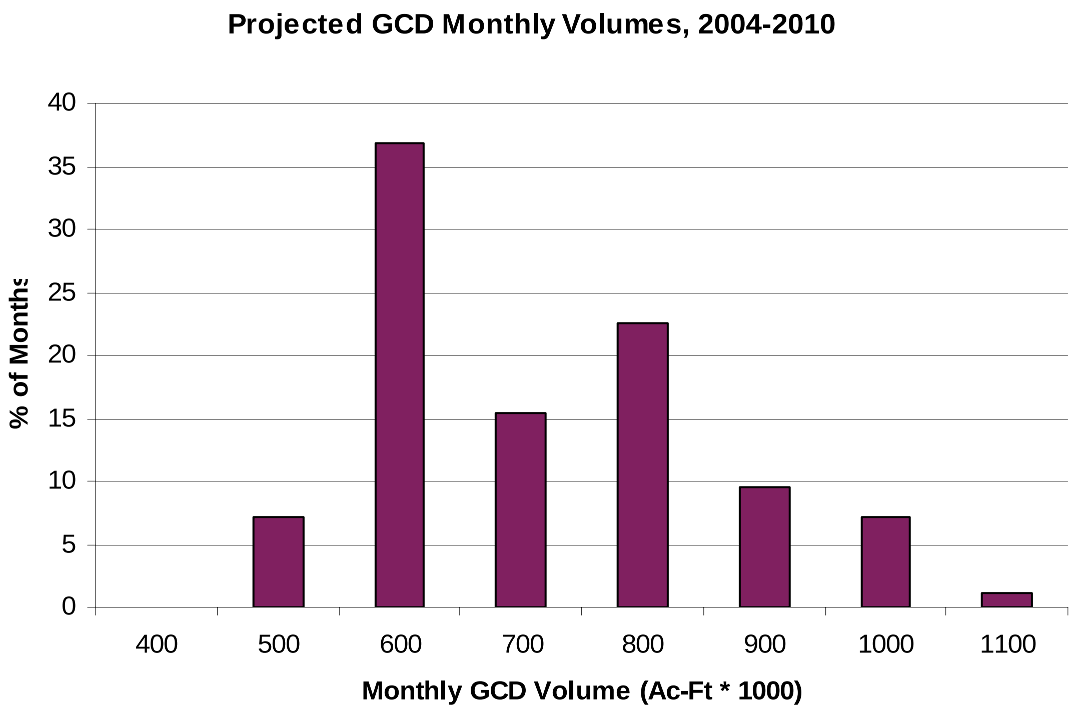


Figure 10. Preliminary numerical simulations of estimated sand-storage responses at three eddies in Marble Canyon under hypothetical experimental fluctuating operations of 5,000 to 25,000 cfs. Part A, is the estimated response at the 22-Mile study site.

A.

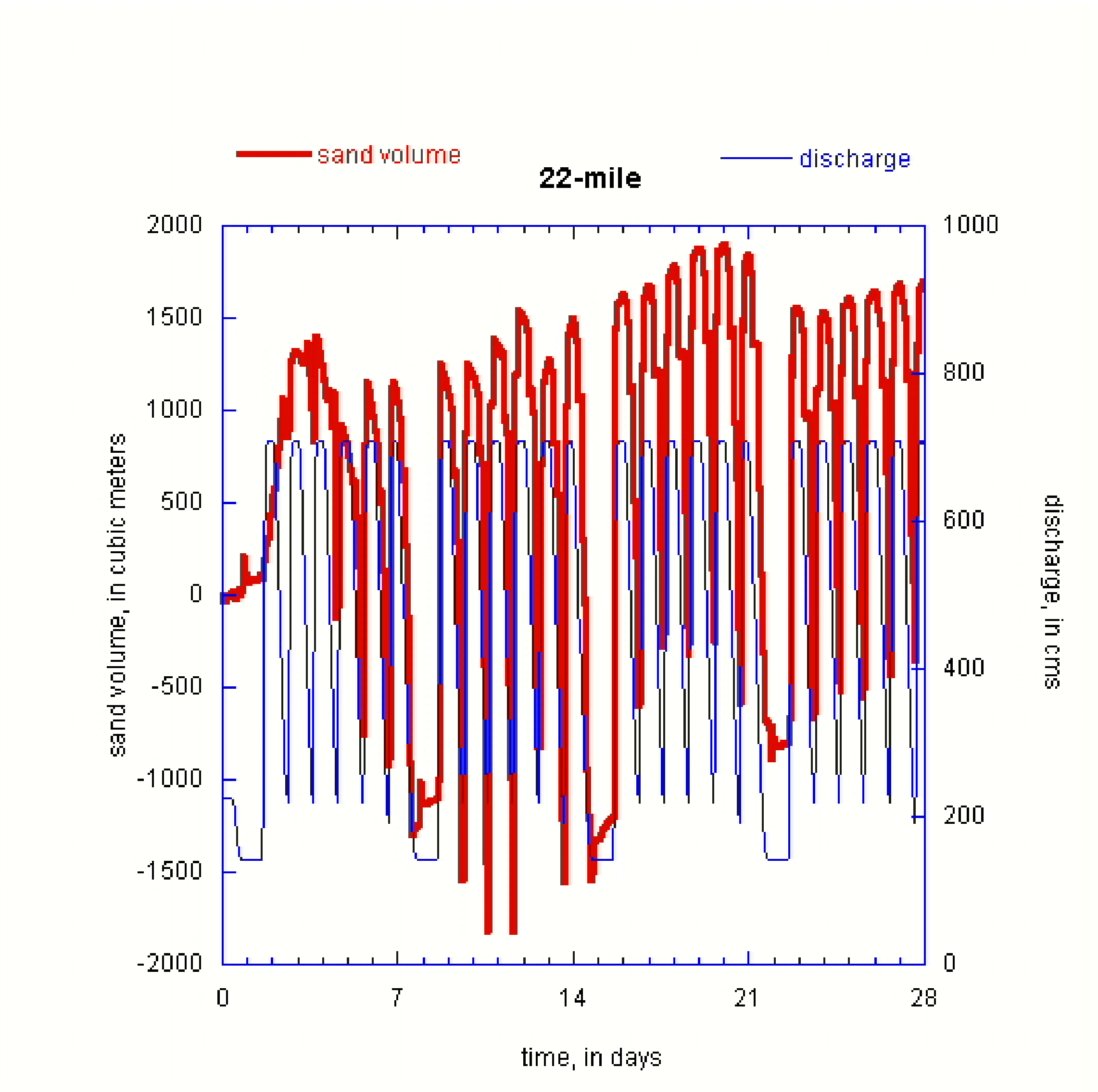


Figure 10. Preliminary numerical simulations of estimated sand-storage responses at three eddies in Marble Canyon under hypothetical experimental fluctuating operations of 5,000 to 25,000 cfs. Part B is the estimated response at the 30-Mile study site.

B.

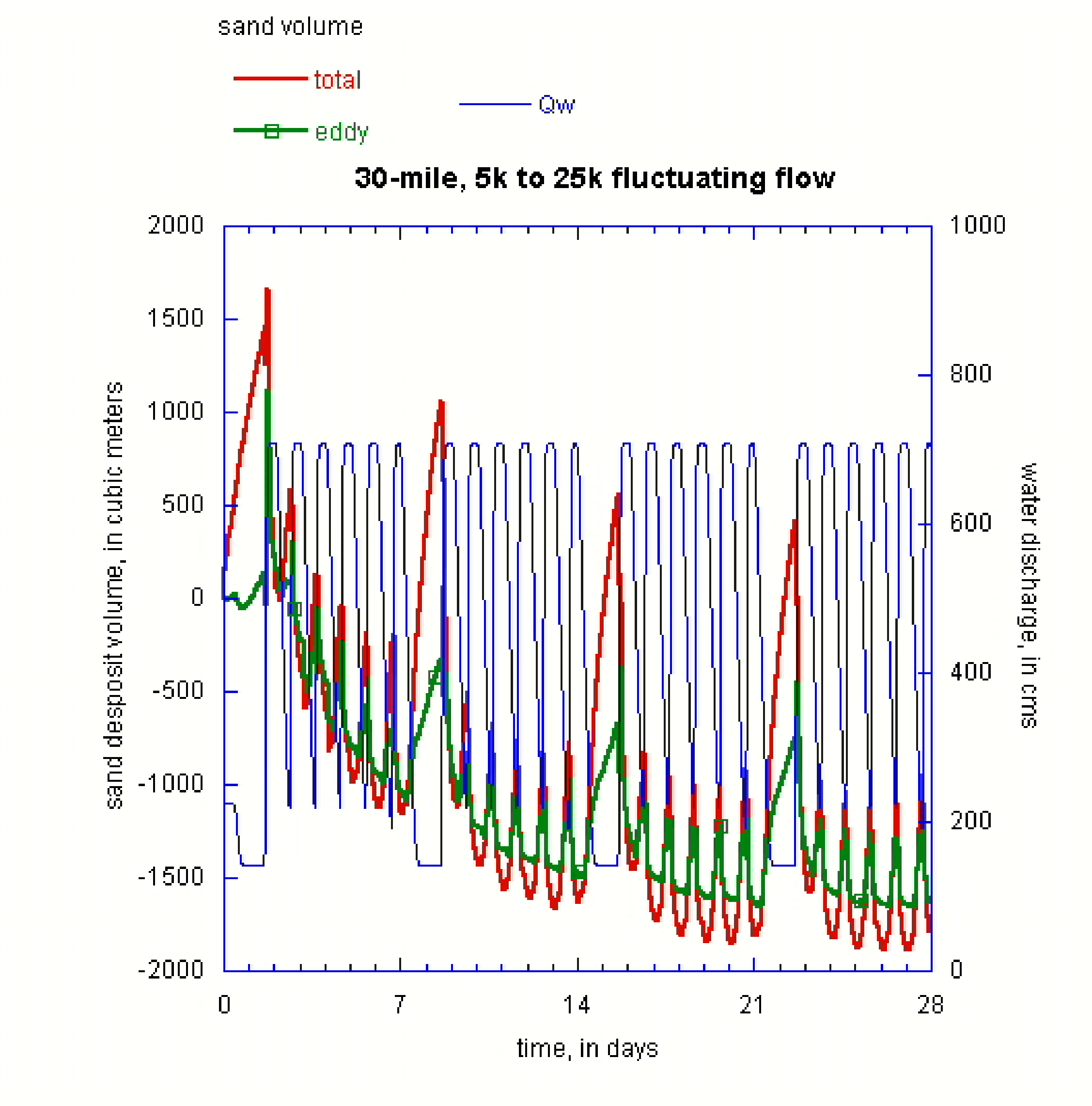


Figure 10. Preliminary numerical simulations of estimated sand-storage responses at three eddies in Marble Canyon under hypothetical experimental fluctuating operations of 5,000 to 25,000 cfs. Part C is the estimated response at the 43-Mile study site (Eminance Break).

C.