Appendix 1. A tally of Glen Canyon Dam Adaptive Management Program experimental surprises.

> *Be "as simple as possible but no simpler" than is required for understanding and communication.*
>
> *Be dynamic and prescriptive, not static and descriptive. Monitoring of the present and past is static unless it connects to policies and actions and to the evaluation of different futures.*
>
> *Embrace uncertainty and unpredictability. Surprise and structural change are inevitable in systems of people and nature.* (Holling 2001:391).

In reviewing Colorado River ecosystem management strategies, Schmidt et al. (1998) conclude that no single approach can improve all river resources valued by society. Resources, such as endangered native fish and large Grand Canyon sandbars, are relicts of the river's pre-regulated flows, sediment supply and thermal regime, but must be co-managed along with artifact resources that only exist because of Glen Canyon Dam and its upstream reservoir, Lake Powell. Artifact resources are also highly valued and include a water supply for millions of southwestern residents (Kenney et al. 2011), hydroelectric energy, a cold, clear water tailwater trout fishery, and annual dam releases that now support popular recreational river rafting year-round. However, sandbar, humpback chub and non-native rainbow trout objectives have been the primary focus of most flow and nonflow experiments since completion of the 1995 environmental impact statement on Glen Canyon Dam operations.

As a basis for further discussion and analysis of surprise learning that has occurred in the Colorado River ecosystem, Table A1.1 provides a tally and cross listing of the main experimental policy treatments (and one unintentional but, informative change – a warmer river) that have been carried out by the Glen Canyon Dam Adaptive Management Program (hereafter, Adaptive Management Program) to date. It does not include information for all 12 of the Adaptive Management Program resource goals within four areas where desired future conditions for the Colorado River ecosystem have been described. Here, we restrict our tally of surprise results mostly to those downstream resources, sediment and aquatic resources, including native fish, non-native fish and the aquatic food base, that have been the main focus of flow and nonflow experimental treatments. Hydropower is also included in Table A1.1, mainly to reflect our view that dam operating changes influence that Adaptive Management Program resource in well understood and highly predictable ways. Table A1.1 does indicate that some downstream resource responses to Adaptive Management Program experimental treatments, such as river stage, water temperature, and Colorado River ecosystem sand budgets, can be estimated (relative increases (+) and (–) decreases) using sub-models that have been calibrated to long-term monitoring data. More importantly, it also identifies the surprises with exclamation marks (!) that have been encountered for each treatment-resource combination, and indicates with question marks (?) those combinations for which there may still be future surprises.

Despite five decades of Colorado River ecosystem studies, surprises may still confront the Adaptive Management Program for a variety of reasons: (1) either appropriate questions have not been asked or data required to answer them may not have yet been collected; (2) appropriate data exist but have not yet been fully analyzed; or (3) experimental treatment effects simply cannot be distinguished from other, uncontrolled "natural" changes acting on key resources, such as flow, sediment supply and river temperature. From our involvement, we conclude that no Adaptive Management Program experimental treatment to date has produced completely unambiguous results, i.e. all available results are confounded to at least some degree by possible effects of uncontrolled factors rather than the intended experimental treatment. Such confounding of effects cannot be avoided in whole system experiments where spatial replication of treatment-control comparisons is impossible, and will likely only disappear very slowly as treatments are replicated under different conditions over time (Walters 1986).

Sandbars

There has been surprise learning among scientists and managers about the effects of high flow experiments (Schmidt and Grams 2011, Melis et al. 2012). Initially, these experimental high releases were expected to increase sandbar camping areas and to restore nearshore backwater habitats created by sandbars within the hundreds of recirculating eddies along the river shorelines (Rubin et al. 2002, Wright et al. 2005, Grams et al. 2010*a*, 2010*b*, Schmidt and Grams 2011). As described in the environmental impact statement (Bureau of Reclamation 1995), high flow experiments were supposed to be occasional flow treatments following multi-year accumulation of tributary sand inputs stored in the deeper parts of the Colorado River ecosystem's main channel. Flow constraints associated with modified low fluctuating flow dam operation after 1996, were intended to achieve multi-year accumulation of the Paria River's fine sand contributions to the Colorado River ecosystem. Later, suspended-sand transport and sandbar grain size monitoring data collected in Water Years (WY) 1996-2004, showed that the hoped for accumulation of tributary sand inputs typically did not occur over multiyear periods in which minimal annual water releases occurred (Rubin et al. 1998, Topping et al. 1999, 2006, Rubin et al. 2002, Wright et al. 2005). Ongoing monitoring showed this to be true, except when annual sand inputs were above average in consecutive years under minimum annual dam releases (Topping et al. 2010). Learning from the initial 1996 high flow experiment resulted in two later tests in November 2004 and March 2008, following a sediment trigger suggested by researchers (Topping et al. 2006).

Surprised initially by these new findings, which occurred almost immediately following the completion of the 1995 environmental impact statement, river managers were eventually convinced by monitoring and research to adopt a "sediment" input trigger for high flow experiment s so that they are only released soon after tributary sand is delivered below the dam (Rubin et al. 2002, Wright et al. 2005, Topping et al. 2006, and Wright and Kennedy 2011). The resulting positive sandbar building responses from the 2004 and 2008 high flow experiment s, then led to approval of the 2012-20 high flow experiment protocol which allows high flow experiments to be released at approximately the same frequency (1-2/yr.) that Paria River floods add new sand to the river (see http://www.gcmrc.gov/gis/sandbartour2013/index.html# for examples of sandbar responses to 2012-14 high flow experiments).

We think that it is key to recognize that this example of adaptive learning by the Adaptive Management Program from surprise outcomes only occurred after more than a decade of ongoing monitoring and research, despite the relatively fast pace of learning by scientists following the 1996 high flow experiment. Although learning may occur quickly following surprises, adaptation may take much longer, as Adaptive Management Program stakeholders required time to assess "useful" new information to the point where it became "usable", and needed sufficient time to consider newly identified "game-changing" trade-offs concerning dam releases (Schmidt et al. 1998, Lemos et al. 2012). Part of the delay in adapting a new flow strategy for Colorado River ecosystem sandbars likely also stemmed from stakeholder needs to consider several trade-offs such as hydropower revenue losses that occur during high flow experiments when water bypasses the powerplant, the ephemeral nature of new sandbars created by those bypasses, and the potential risk of "robbing Peter to pay Paul" by increasing sandbar area in upstream river segments while also exporting sand to Lake Mead from beaches further downstream (Topping et al. 2006, Hazel et al. 2010, Grams et al. 2010*a*).

Another lesser high flow experiment flow treatment originally intended to modify shoreline habitats, such as nearshore backwaters, the habitat maintenance flow does not require bypass releases, as higher peak-discharge high flow experiments do since these flows are released from the dam at peak powerplant capacity. Three habitat maintenance flow tests have occurred since modified low fluctuating flow operations started (November 1997, and May and September of 2000 as part of the low summer steady flow experiment). Sandbar monitoring data suggest that habitat maintenance flows may also help conserve sandbars, but to a lesser extent than higher peak high flow experiments (Hazel et al. 2006, 2010). Scientists later determined from monitoring and modeling analyses that rainbow trout recruitment in Glen Canyon National Recreation Area was increased in 2000, the year that one of the habitat maintenance flows was tested during spring (Korman et al. 2012), but none of the three habitat maintenance flows appear to either have directly benefited native fish in Grand Canyon National Park through near-shore habitat improvements as proposed in the 1995 environmental impact statement (Ralston 2011).

It now seems clear that if Colorado River ecosystem sandbars are to be rebuilt and maintained through the adaptive high flow experiment protocol, then such dam operations must occur more frequently than originally suggested in the environmental impact statement, but how often to achieve desired sandbar area conditions is not clear. In contrast to recent criticisms about the program's progress (Susskind et al. 2012), the more flexible experimental strategy for sandbar conservation is a prime example of the Adaptive Management Program's ability to adapt to surprise learning in the face of uncertainty; albeit over a relatively long period of monitoring and research. The new high flow experiment protocol annual decision process is also closely tied to new monitoring and modeling that provides a good example of improvements in using science to support Adaptive Management Program goals (Grams et al. 2015). Trade-offs associated with this adaptive shift in experimental sandbar conservation are still being evaluated among Adaptive Management Program stakeholders; a process that will likely be influenced by sandbar data as testing continues under changing climate.

Table A1.1. A cross listing of Adaptive Management Program experimental treatments (columns) arranged roughly by time of application (1996 to 2015), and surprising results reported to stakeholders, and (or) lingering uncertainties identified by river managers, and scientists related to a subset of Colorado River ecosystem resources (rows) generally listed in relative order of low to higher predictive uncertainty. Exclamation points (!) indicate surprise results, that were not generally anticipated in the environmental impact statement (Bureau of Reclamation 1995), or predicted by the Grand Canyon ecosystem model (Walters et al. 2000), and may be sources of new or lingering questions/hypotheses indicated by question marks (?) resulting from confounding factors, a lack of appropriate monitoring data, or limited analysis, such that predicted responses have remained highly uncertain. Plus (+) and minus (-) signs indicate the relative measured responses of resources to treatments. Double symbols indicate greater responses.

Subset of Key AMP Resources & EXP Treatments	**High Flow Experiments**	**Modified Low Fluctuating Flows**	**Habitat Maintenance Flows**	**Low Summer Steady Flows (JUN-SEP)**	**Trout Management Flows (winter tests)**	**Remove Non-native Fishes (GRCA)**	**Warmer Releases from Lake Powell**	**Fall Steady Flows (SEP-OCT)**	**High Steady Flows**
Hydroelectric Energy (daily peaking)	-	--	-	--	+	**N/A**	**N/A**	-	--
GRCA Sandbar Area	++	-/!!	+	+	--	**N/A**	**N/A**	+	-
GLCA Rainbow Trout	!!/+/?	+/!	?/+	!/+	!	**N/A**	!!/+/?	!!/+	!!/+
Aquatic Food Base	!!/+/?	+/?	?	?	?	?	!/?	?	?
Native Fish (humpback chub)	!/?	!/?	!/?	!/?	?	!!/?	!!/?	!/?	!/?
Warm Water Exotic Fish	?	?	?	+	?	?	?	?	?

Native Fish

A great deal of interest among Adaptive Management Program managers has been devoted to the many surprises (!) and remaining uncertainties (?) for native and non-native warm water fish responses shown in Table A1.1. Wider-ranging diurnal flow fluctuations termed “research flows” that occurred during 1990-91, were a year-long series of varying dam operations, each of about two weeks duration, and included a range of dam release patterns studied to inform the 1995 environmental impact statement. The modified low fluctuating flow regime was predicted to result in reduced sandbar erosion rates and moderate improvements in Colorado River ecosystem shoreline morphologies supporting mainstem nursery conditions; features predicted to enhance juvenile native fish recruitment. Available data used for native fish recruitment reconstructions indicate exactly the opposite responses initially (Fig. A1.1), with high humpback chub recruitments associated with pre-modified low fluctuating flows (1987-91) and stable or declining recruitment over the initial 1991-95, low fluctuating flow dam operations (termed “interim flows”) that preceded modified low fluctuating flow in 1996. Further, indices of young-of-year (YOY) humpback chub abundance indicate production of at least two very large juvenile cohorts within the Little Colorado River (1991, and 1993) and relatively high YOY abundances in the mainstem during the 2000 low summer steady flow experiment (Coggins et al. 2006*a*, 2006b, Coggins and Walters 2009, Ralston 2011). These high early juvenile abundances were expected to result in increased recruitments to the older (age-4+, adult) population, but no such increases occurred (Fig. A1.2), suggesting strong density-dependent mortality of juvenile chubs after their first summer of Little Colorado River and (or) Colorado River ecosystem rearing.

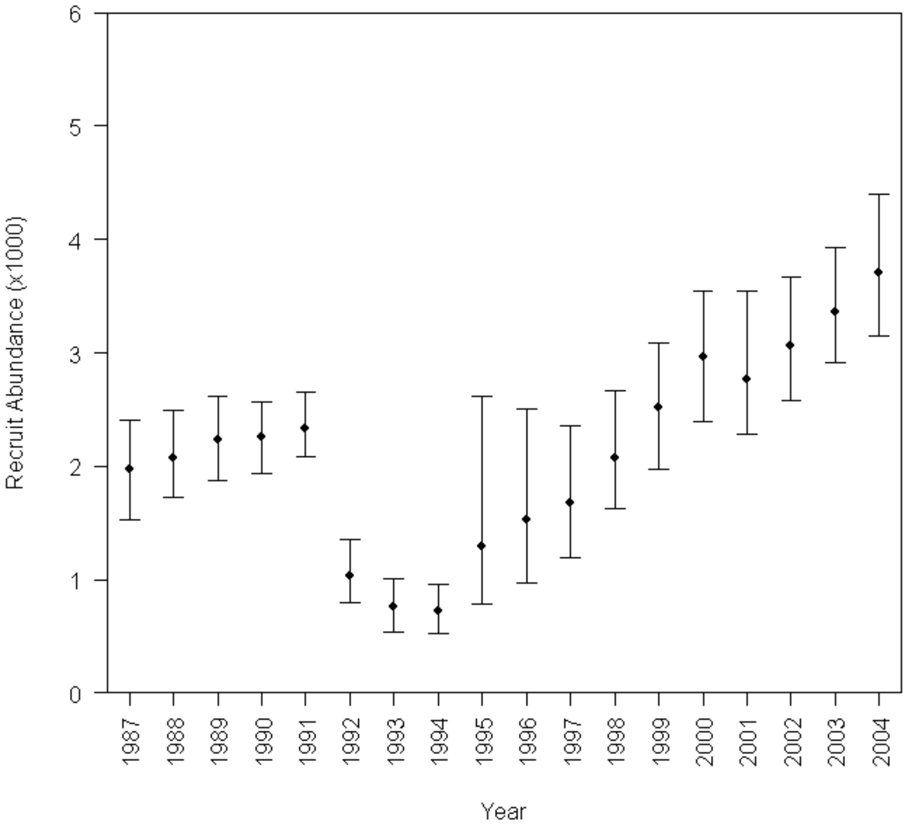


Figure A1.1. Estimated recruit abundance (age-2) of humpback chub in the Little Colorado River population of Grand Canyon National Park, from Coggins and Walters (2009). Estimates are from mark-recapture analysis of passive integrated transponder (PIT) tagging data (Coggins et al. 2006*a*). Error bars show effect on the estimates of aging error due to estimating fish ages from lengths since destructive sampling for structures that carry age information (e.g. otoliths) has typically not been allowed for this endangered species.

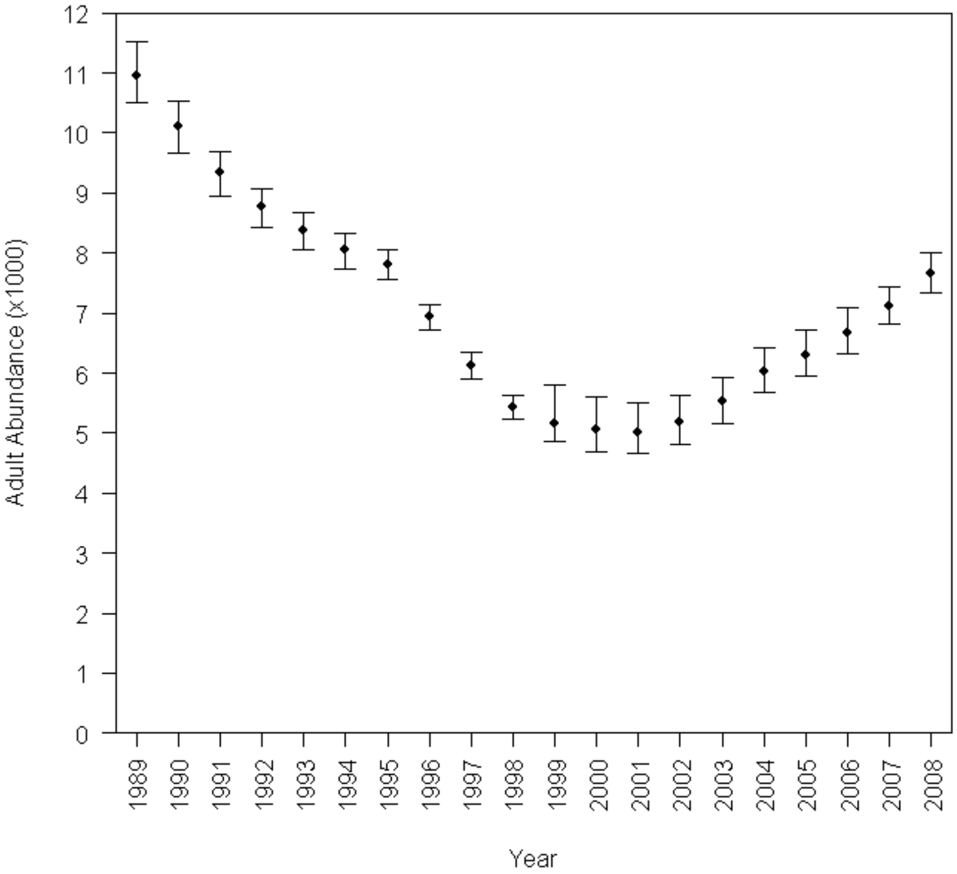


Figure A1.2. Adult abundance (age-4+) of humpback chub in the Little Colorado River population of Grand Canyon National Park, from Coggins and Walters (2009). Estimates are from mark-recapture analysis of PIT tagging data (Coggins et al. 2006*a*). Error bars show effect on the estimates of aging error due to estimating fish ages from lengths since destructive sampling for structures that carry age information (e.g. otoliths) is not allowed for this endangered species.

Further evidence for strong density dependence in juvenile survival comes from long term monitoring data on juvenile humpback chub abundances in the Little Colorado River spawning and rearing areas, which show that for the period between 2001 and 2008, there was a two year recruitment cycle with strong age-1 juvenile abundances perhaps causing reductions in age-0 survival rates in alternate years (Fig. A1.3). The 2-year cycle appears to break down after 2009, but the highly variable annual chub production in the Little Colorado River reported by Van Haverbeke et al. (2013) between 2001-14, does not bode well for managers who hope to detect recruitment responses quickly after short experimental treatments focused on native chub are started. Net recruitment of native fish to older ages does appear to have responded positively over the 2003-06 treatment period of experimental non-native fish removal from the Colorado River ecosystem mainstem near the Little Colorado River confluence (Coggins et al. 2011). But this response could also be due to coincident increases in water temperature that occurred as a result of low water levels in Lake Powell (Fig. A1.4), resulting from repeated years of upper Colorado River basin drought after WY 2001 (Melis et al. 2006, Voichick and Wright 2007, Vernieu 2013). An additional confounding factor associated with the 2003-06, non-native fish removal experiment in Grand Canyon National Park and increased native fish abundance after about 2000, is the system-wide decrease in rainbow and brown trout (*Salmo trutta*) abundance that apparently began prior to the 2003-6, non-native fish removal experiment (Makinster et al. 2010, Coggins et al. 2011, Makinster et al. 2011).

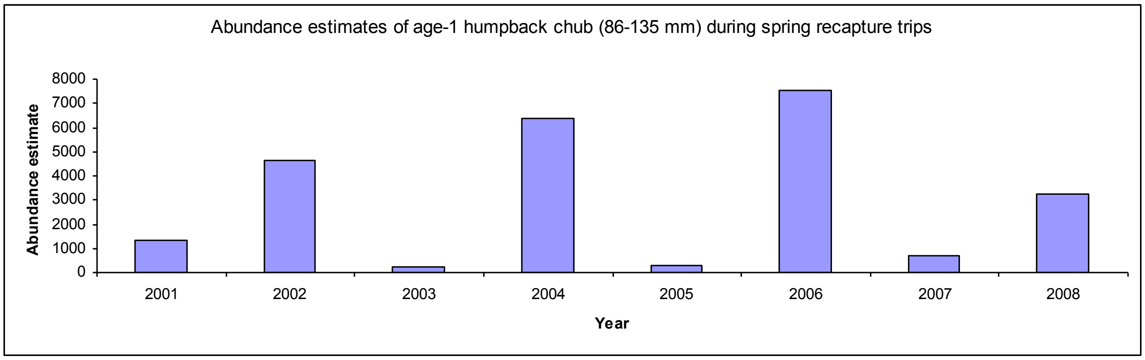


Figure A1.3. Abundances of age-1 humpback chub in the Little Colorado River (R. Van Haverbeke, U.S. Fish and Wildlife Service, and L. Coggins, USGS, pers. comm., 2010).

Naturally warmer water releases from Lake Powell after WY 2002 (Fig. A1.4) provided an opportunity to test the previously mentioned Grand Canyon ecosystem model prediction that non-native fishes might increase dramatically should the river be deliberately warmed through operation of proposed, but never constructed selective withdrawal structures on the dam, so as to cause long term negative impact on native fish recruitment. But it may not be possible to capitalize on this unplanned ongoing "warming experiment", due to challenges in monitoring larger non-native warm water fish below Glen Canyon National Recreation Area. The synoptic spatial sampling for fish abundances along the Colorado River ecosystem (electrofishing, hoop netting, beach seining, and trammel netting until recently) catches very few of those large non-native fish, and it's not possible to tell whether this is due to low capture efficiency or low ongoing abundances. The long term data suggest that common carp (*Cyprinus carpio*) and channel catfish (*Ictalurus punctatus*) have been decreasing slowly over time due to poor reproductive success in the cold mainstem water, but these data are very noisy. The data show no clear indications that recruitments of at least carp and catfish have increased following onset of the warm water period after 2002, though the data do show strong increases in native bluehead and flannelmouth sucker (*Catostomuus discobolus* and *latipinnis*, respectively) species (Makinster et al. 2010, Walters et al. 2012).

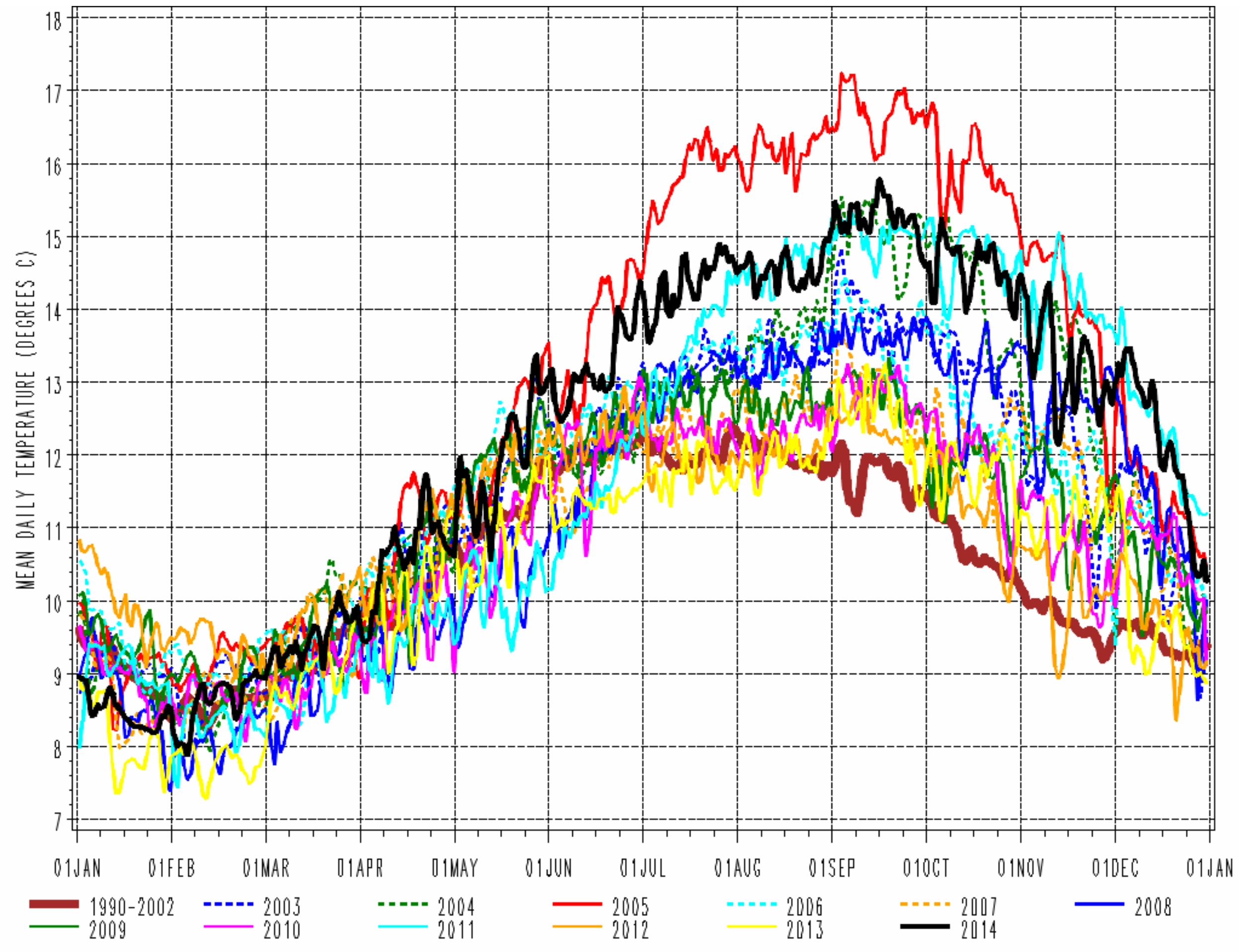


Figure A1.4. Long-term average (1990-2002) and annual trends of mean daily Colorado River ecosystem water temperature (data from US Geological Survey, Grand Canyon Monitoring and Research Center, after Voichick and Wright 2007) 122 km below the dam measured just upstream of the Little Colorado River confluence (2003-14). Following nine years of variable but relatively warmer downstream river temperatures, WY 2012-13 temperatures near the Little Colorado River were closer to the 1990-2002 average following Glen Canyon Dam releases in 2011 (annual dam releases in 2011, 2012 and 2013 were 15.4, 11.7 and 10.2 billion cubic meters, respectively). River temperatures near the Little Colorado River in WY 2014 were warmer in spring, similar in summer, but cooler in fall to winter compared to WY 2011 under the lowest annual dam release volume (9.2 billion cubic meters) since 1964. Such continuing year-to-year variation in the river's thermal regime presents opportunity for experimental learning about aquatic resource responses to dam operation. (plot provided by W. Vernieu, US Geological Survey).

Perhaps the single most surprising "experiment" in the Adaptive Management Program to date was the previously mentioned low summer steady flow experiment of 2000 (Table A1.1), intended to warm mainstem Colorado River ecosystem shorelines proposed to be critical native fish nursery habitats below the Little Colorado River confluence. It apparently resulted in relatively large increases in sampled relative abundances of small (juvenile and small bodied) fishes, which then largely disappeared when the steady flow experiment abruptly ended in October that year (Ralston 2011). It is not entirely clear whether juvenile fish abundances actually did increase, since increases in catch rates could have been due simply to improved performance of the sampling gear (higher "catchability") under lower stable summer flows. But another key and unexpected system response was revealed, namely the formation of nearshore thermal hotspots. These formed at water's edge along sand and gravel shorelines owing to solar insolation during the intense heat of summer in Grand Canyon National Park. These pockets of warmer water in nearshore areas reached up to 27º Celsius near the water surface during daylight hours but then cooled quickly after sunset (Vernieu and Anderson 2013). During the 2000 low summer steady flow experiment, these thermal features might have created small, ephemeral refuges for juvenile native fishes in an otherwise unsuitably cold river resulting from hypolimnetic dam releases of 9-10º Celsius from Lake Powell that summer. We suspect that "surprise" about the degree to which nearshore temperature could be influenced through steady shoreline habitats in summer months may have influenced a later decision to implement the fall steady flow experiment (Grand Canyon Monitoring and Research Center 2008). The fall steady flow treatment followed several years after the low summer steady flow experiment and was approved for annual testing in September through October, 2008-2012, but it was also confounded owing to the fact that it mostly occurred during a period of warmer dam releases than occurred in 2000 (Fig. A1.4).

Not intended as a thermal management treatment, managers were interested in determining whether steady fall flows timed to coincide with periods when Little Colorado River juvenile native fish typically enter the Colorado River ecosystem from this tributary spawning habitat, might improve chub recruitment. Such questions surrounding use of stable and (or) warmed shoreline areas by native fish became an Adaptive Management Program stimulus for developing substantial new experimental research on nearshore aquatic ecology in Grand Canyon National Park, such as the nearshore ecology of humpback chub being the research project associated with the 2008–12 fall steady flow experiment. The low summer steady flow experiment also resulted in an above average cohort of rainbow trout fry in the Glen Canyon National Recreation Area recreational fishery, and these juveniles may have caused an abundance peak in larger fish in 2003, but apparently did not have a persistent effect on the population, and (surprisingly) showed little evidence of outmigration downstream from Glen Canyon National Recreation Area into Grand Canyon National Park (Makinster et al. 2010, 2011, and Korman et al. 2012).

Non-native Rainbow Trout

Besides surprises about sandbars and native fish, introduced sport fish responses have also provided learning opportunities, but over a longer period owing perhaps to the Adaptive Management Program's greater initial emphasis on resources in Grand Canyon National Park relative to Glen Canyon National Recreation Area resources upstream of Lees Ferry. The Glen Canyon National Recreation Area's rainbow trout population in the 25 km long tailwater fishery below the dam and in the 98 km long segment of Marble Canyon in Grand Canyon National Park has exhibited surprising changes that may be indicative of long term shifts in aquatic ecosystem structure (Fig. A1.5).

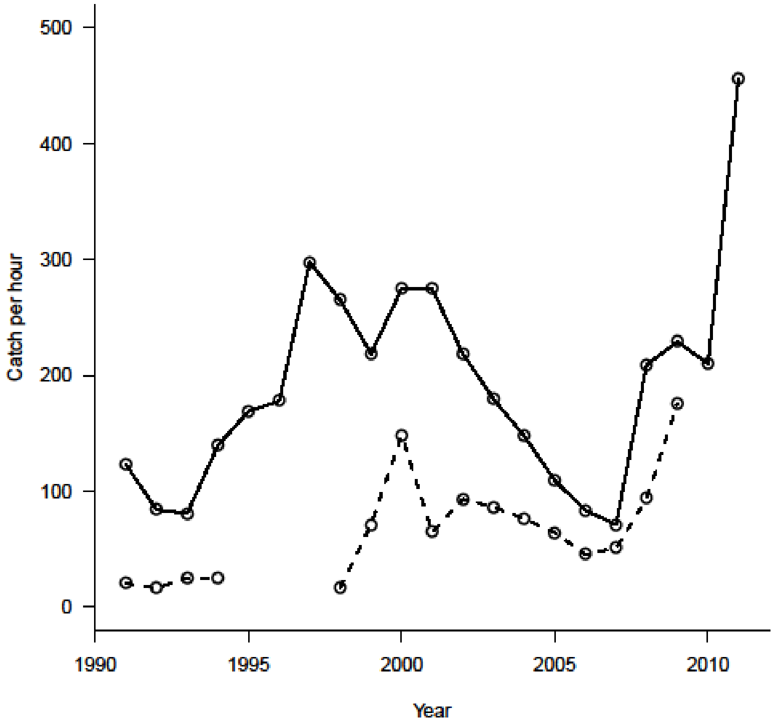


Figure A1.5. Relative abundance of Glen Canyon National Recreation Area rainbow trout (solid line) between Glen Canyon Dam and Lees Ferry, and Grand Canyon National Park rainbow trout (dashed line) between the Paria and Little Colorado River confluences with the Colorado River. Estimates are mean electrofishing catch rates from multiple sample stations. Note that most fish were hatchery plants prior to 1990 and mostly wild-spawned afterward (data from US Geological Survey, Grand Canyon Monitoring and Research Center, after Makinster et al. 2011, 2010).

Before the 2000 low summer steady flow test, trout population there increased over the 1990s, apparently in response to improvements in food base and juvenile nursery conditions associated with steadier flows under modified low fluctuating flow (McKinney et al. 2001). That population responded pretty much as rainbow trout might be expected to respond to increases in their food base and juvenile nursery conditions associated with research flows and re-operation of the dam to modified low fluctuating flows. Generally, rainbow trout populations tend to exhibit "biomass conservation", in the sense that population biomass tends to stabilize at some level apparently set by total food production (mainly drifting and emerging aquatic insects). But where numerical recruitment rates are low (low stocking rates, lack of spawning or nursery area, low juvenile survival rates due to competition/predation interactions), the overall biomass consists of small numbers of large fish; where numerical recruitment is high, the biomass consists of large numbers of small fish. Following adoption of modified low fluctuating flow operations in the mid-1990s, biomass and numbers both increased (more food production under reduced diurnal flow fluctuations, and better juvenile survival). Then two substantial surprises occurred:

1) growth was expected to improve with the warming that occurred as Lake Powell storage dropped after 2002 (Figs. A1.4 and A1.5); instead, trout appeared to be starving and there was an apparently large mortality partly associated with both Lake Powell water quality and dam releases that affected the Glen Canyon National Recreation Area fishery in 2005 (widely fluctuating emergency dam operations in late June that were later followed by dam releases with quite low dissolved oxygen conditions in the fall);
2) there was a progressive decline in the trout population (and biomass) in both Glen Canyon National Recreation Area and Grand Canyon National Park over a five year period until about 2007, despite apparently favourable flow conditions for food base production, then an increase in population that was driven by a spring-timed high flow experiment in 2008 (Korman et al. 2012), as well as quite warm and large volume releases from Lake Powell required in 2011, to equalize downstream storage in Lake Mead (Figs. A1.6 and A1.7, M. Yard, US Geological Survey, written commun., 2015).

The second of these responses is a good example of a surprise that might be used to trigger development and testing of alternative hypotheses about how aquatic ecosystem function is changing in the Glen Canyon National Recreation Area tailwater fishery just below the dam (and might change in downstream areas of Grand Canyon National Park under some future policy options such as those favoring sediment objectives). There are several plausible hypotheses for the 2001-06 Colorado River ecosystem biomass decline:

1) there may have been a progressive decline in overall primary and secondary productivity in the Glen Canyon National Recreation Area tailwater, due to declining nutrient loadings associated with release of nutrient-depleted surface waters from Lake Powell;
2) there also may have been a decline in the proportion of primary production usable by insects and amphipods, due to successional replacement of filamentous algae (*Cladophora glomerata*) by high biomass/slow turnover macrophytes and bryophytes;
3) an increasing proportion of primary production may have ended up just building biomass of an invader species, such as the New Zealand mud snail (*Potamopyrgus antipodarum*), which is a relatively poor food for rainbow trout (Cross et al. 2011);
4) following a three-year period of almost no Paria River floods, more frequent fine-sediment inputs from that downstream tributary to Marble Canyon in 2004-7 may have further reduced suitable conditions for trout below Glen Canyon National Recreation Area (Coggins et al. 2011, Fig. 7).

The 2001-06, rainbow trout decline (Makinster et al. 2010, 2011) is also a good example of why we cannot trust the predictions from ecosystem models like the Grand Canyon ecosystem model. The macrophyte/bryophyte replacement and New Zealand mud snail hypotheses are examples of what ecological modelers call “vampires in the basement”, state variables that were not considered important enough to include in the initial model development and that only emerge to become important later on as a result of carefully planned and consistent monitoring and research implemented by the Grand Canyon Monitoring and Research Center since the Grand Canyon ecosystem model was developed (Cross et al. 2013). The biological diversity of ecosystems ensures that there is an endless list of such variables. We could of course add them to the Grand Canyon ecosystem model in hindsight, but it might make more sense to establish their importance to functioning of the rainbow trout production system directly through ongoing field studies that continue to be carried out by the Grand Canyon Monitoring and Research Center, without reliance on an improved ecosystem model.

As previously mentioned, the widely publicized March 2008 high flow experiment had a surprisingly positive effect on the Glen Canyon National Recreation Area trout population (Korman et al. 2012, 2011, and Kennedy and Ralston 2011, Melis et al. 2012), that was apparently linked to increased availability of two benthic invertebrate taxa (Cross et al. 2011). Recreational anglers were pleasantly surprised in 2009, to find larger, healthier (fatter) rainbow trout than in recent years, apparently signalling a welcomed trout recovery in the Glen Canyon National Recreation Area fishery. Further, the trend toward macrophyte/bryophyte dominance of the benthic production system was apparently reversed by the 2008 high flow experiment, at least temporarily, with lush Cladophora growth and dramatic emergence of aquatic insects (mainly simulids) in 2009 (Rosi-Marshall et al. 2010). It appears that the spring-timed high flow experiment provided a strong “reset” of the aquatic production system, by removing older and less productive plants, scouring away recently accumulated fine sediment and detritus around the base of plants (creating more interstitial microhabitat for invertebrates), and carrying away large numbers of New Zealand mud snails (Rosi-Marshall et al. 2010, Cross et al. 2011, Melis et al. 2012).

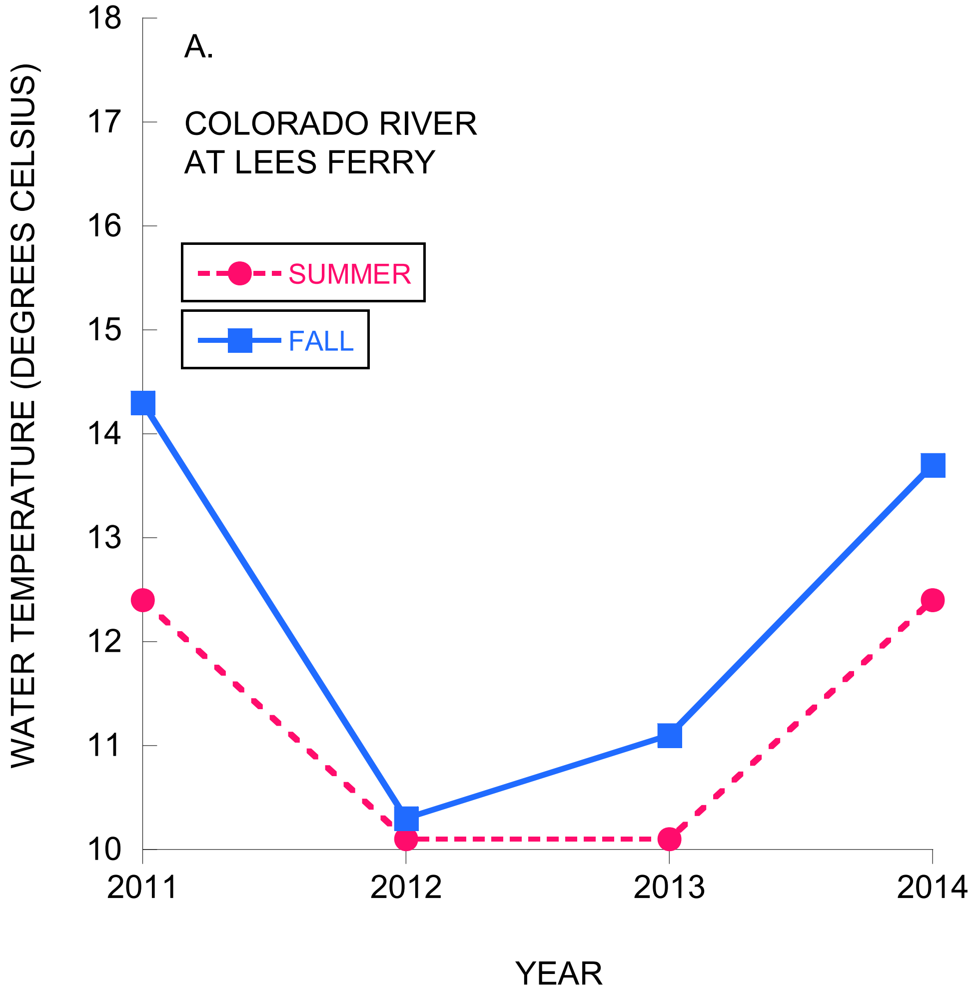
Integrating Adaptive Management of Sandbars and Fish with Dam Operations

Whatever the precise mechanism, it now appears that high flow experiments could have beneficial effects for the Glen Canyon National Recreation Area fishery and sandbars, but also possibly indirect negative downstream effects on native fish resulting from increased competition for limited habitats and food availability, and predation from rainbow trout that either out-migrate downstream or are locally produced in Grand Canyon National Park (Fig. A1.5). Hence, a more complicated challenge in co-managing native and non-native fish clearly exists in the Colorado River ecosystem than may have previously been recognized by managers, but one that appears to be tied to dam operations – the original focus of the Adaptive Management Program when it was established in 1997. Surprise Adaptive Management Program learning about trout responses to high flow releases in the Colorado River ecosystem also appears to concur with recent findings of Robinson and Uehlinger (2008) about use of increased experimental high flows to improve a brown trout fishery below a Swiss dam. More recent research by Mims and Olden (2012, 2013) about fish life history strategies and fish assemblage responses to flow regimes also helps explain benefits to rainbow trout under modified low fluctuating flow and high flow experiments. In hindsight, perhaps surprise learning about the Glen Canyon National Recreation Area tailwater fishery should not have been so surprising, but modeling did not predict how sensitive this salmonid fishery would be to dam re-operation; particularly, combining steadier daily operations with spring high-flow releases. Without consistent multidisciplinary monitoring following experimental re-operation of Glen Canyon Dam in 1990s, and carefully integrated studies of each of the first several high flow experiments, surprise learning about trout, food web and sandbar dynamics would have been very unlikely.

From monitoring of experimental dam releases, including repeated high flow experiments in either spring or fall seasons, it appears that Grand Canyon humpback chub are robust to experimental dam releases, at least for the limited flow treatments that have been tested to date (Kennedy and Ralston 2011, Finch et al. 2013). However, variations in river temperature and abundance of non-native trout relative to native fish recruitment have provided new insights. So far, Adaptive Management Program observations of native fish recruitment since 1990 have mainly occurred under two temperature and trout predation conditions: (1) relatively colder dam releases/higher downstream trout abundance, and (2) relatively warmer dam releases/lower downstream trout abundance (Table 2). Relatively poorer humpback chub recruitment during the first few years of intensive Colorado River ecosystem monitoring (1991-93), apparently before trout became abundant in the mainstem near the Little Colorado River confluence, suggests that lower dam release water temperatures may result in poor chub recruitment when trout abundance remains low in the mainstem near the Little Colorado River as a result of non-native fish control measures or other factors, such as increased delivery of tributary fine-sediment and dam operations that promote sandbar conservation, influencing downstream trout abundance in Grand Canyon National Park.

Following the variable but warmer dam releases of 2003-11, relatively colder releases returned briefly in 2012-13 (Fig. A1.4), followed by warmer summer and fall dam releases again in 2014 (Fig. A1.6); the lowest annual volume released from Glen Canyon Dam since 1964 (Fig. A1.7). On the basis of preliminary fish monitoring, rainbow trout abundances in Glen and Marble Canyons, as well as near the Little Colorado River have been reported to the Adaptive Management Program by scientists to have increased since about 2010. These increases in the Glen Canyon National Recreation Area trout fishery resulted from the spring 2008 high flow experiment (Korman et al. 2012), and high and steady releases in 2011 required to transfer water from Lake Powell to Lake Mead (see preliminary data presented by Yard and Korman: http://www.usbr.gov/uc/rm/amp/twg/mtgs/15jan20/Attach_18.pdf). Downstream increases of rainbow trout in Grand Canyon National Park have been reported to the Adaptive Management Program since 2011, and are apparently the result of poorly understood, but episodic outmigration from Glen Canyon National Recreation Area in 2011, on the basis of preliminary movement studies conducted in 2012-14 (see preliminary data presented by Korman and Yard:

http://www.usbr.gov/uc/rm/amp/twg/mtgs/15jan20/Attach_12.pdf). Downstream trout abundance may also be increasing from some yet-to-be determined level of local production below the Glen Canyon National Recreation Area tailwater on the basis of Grand Canyon Monitoring and Research Center's 2014 annual reporting to Adaptive Management Program stakeholders. If management of release temperatures at Glen Canyon Dam were currently possible, then maintaining the warmer releases of 2014 for several years as downstream trout increase would provide critical information about the relative limiting roles of temperature versus non-native predation in juvenile humpback chub recruitment.



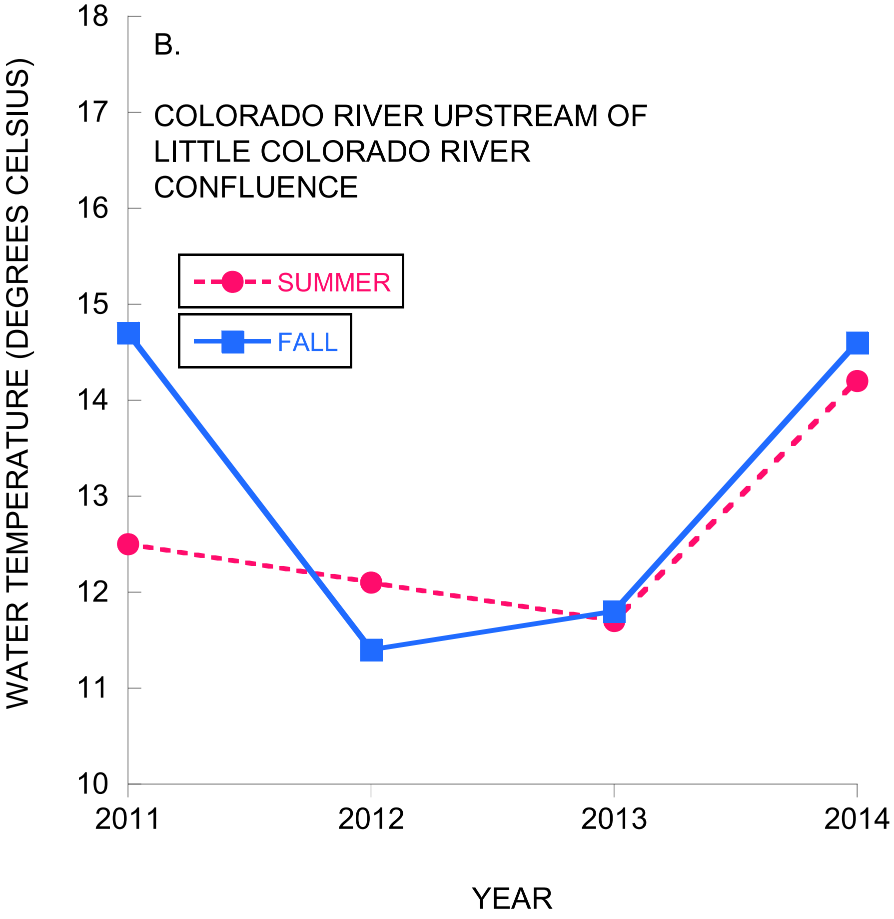


Figure A1.6. Median 2011-14 summer (June-August) and fall (September – November) water temperatures of the Colorado River measured at US Geological Survey streamgages 09380000 and 09383100, located (A) 25 km (at Lees Ferry) and (B) 122 km (near the Little Colorado River confluence) downstream of Glen Canyon Dam. (data: http://www.gcmrc.gov/discharge_qw_sediment/stations/GCDAMP).

The Grand Canyon ecosystem model or other models cannot reliably predict what would happen under the lower temperature/lower trout condition, i.e. we cannot reliably predict whether continued trout control efforts, those previously tested or other variants (Coggins et al. 2011, Korman and Melis 2011), will result in improved native fish recruitment whenever those river conditions return in the future; as they did briefly in 2012-13 (Fig. A1.6). Available models

(Peterson and Paukert 2005, Yackulic et al. 2014) suggest that juvenile growth rates would be reduced by colder water, which could lead to longer exposure to high predation risk, but we do not know for certain if, or to what degree juvenile chub might partially compensate for this by periodically moving upstream and back into their Little Colorado River natal origin habitat from the mainstem (Limburg et al. 2013, Yackulic et al. 2014).

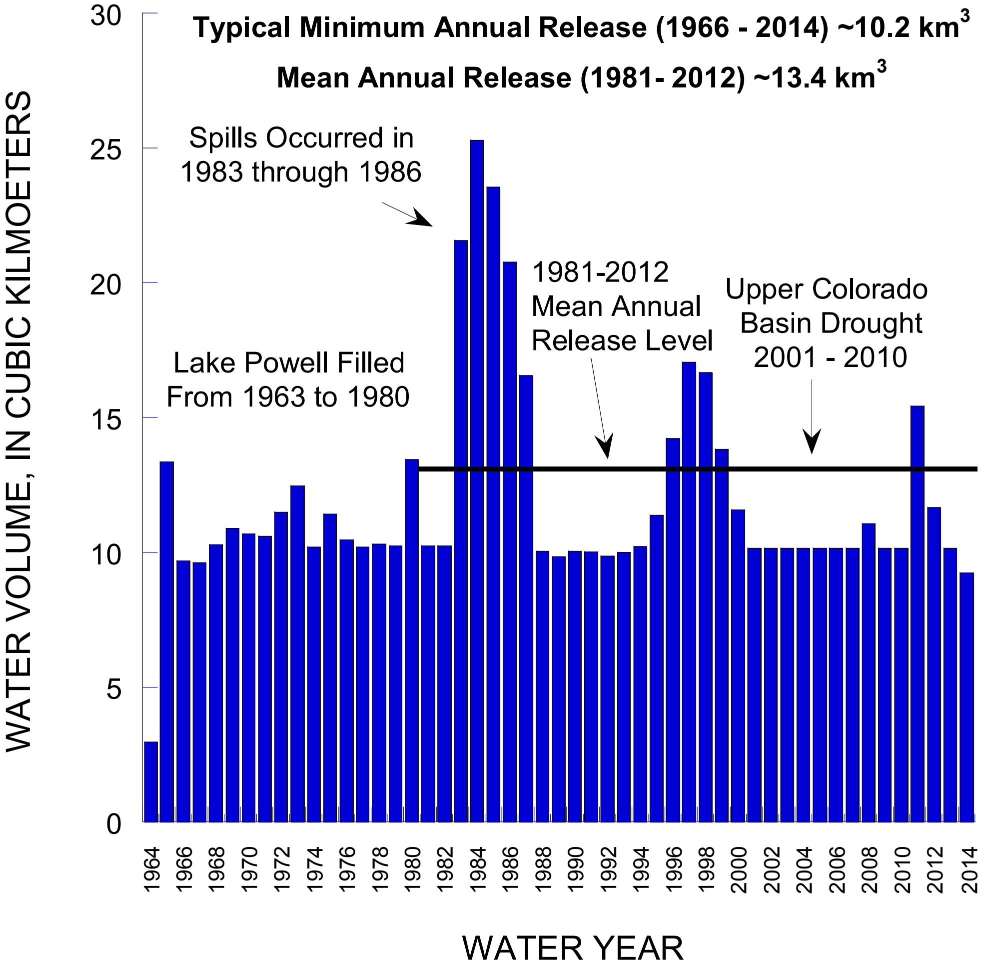


Figure A1.7. Annual water volumes released through Glen Canyon Dam from Lakes Powell to Mead (1964-2014) (data courtesy of R. Clayton and K. Grantz, written commun., 2014, U.S. Department of the Interior, Bureau of Reclamation).

Further, increases in food availability absent competition with trout may partially compensate for Colorado River ecosystem temperature effects on juvenile chub growth near the Little Colorado River. We know that ability to escape predators, and likely ability to avoid downstream dispersal into reaches populated by brown trout near Bright Angel Creek (located about 163 km below the dam, Fig. 1), are likely to be reduced by colder mainstem water, but we do not know whether this will lead to increased predation by other known predators besides trout (particularly older humpback chub). So we can only really construct plausible models based on available physiological and behavioral data, and possible food base changes that predict either a strong positive effect of low trout abundance or no effect at all. Also somewhat of a surprise, scientists have not reported any hoped for changes in the Colorado River ecosystem food web diversity as might be predicted under observed river warming that has occurred since 2003 (Kennedy et al. 2013, Table A1.1).

Even more importantly, current ecosystem modeling cannot predict what might happen under the now-emerging conditions of warmer water temperature/higher trout abundance. Rainbow trout abundance near the Little Colorado River has only recently increased after about 2010, and humpback chub juvenile survival data are only now being collected by Grand Canyon Monitoring and Research Center researchers who may not yet have had sufficient time to fully evaluate this previously unobserved condition (Tables A1.1, Table 2, Figs. A1.5, and A1.6). It is entirely possible that this condition would result in high mainstem recruitment of native fish, i.e. warm water may be sufficient to maintain high recruitment even if trout control measures are not effective in either Glen Canyon National Recreation Area or Grand Canyon National Park.

There is one thing that we believe can be more confidently predicted: that if temperature changes do result in decadal periods of high versus low native fish recruitment as have occurred over the last two decades, then it will likely not be possible to achieve the Adaptive Management Program's goal of maintaining an adult chub population of at least 6,000 fish in the Little Colorado River alone (Yackulic et al. 2014, Fig. 5). Under any reasonable parameter combinations for survival and fecundity of older fish, individual-based population viability models predict that alternation of high and low recruitment periods similar to the 1990s vs. 2000s periods will likely result in average adult population sizes well below the current population target (Pine et al. 2013).

Our Table A1.1, and this narrative are not meant to be an exhaustive review of policy tests and resource responses in the Colorado River ecosystem. Rather, they are intended to help guide ongoing discussions by Adaptive Management Program participants about several complicated resource and management trade-offs, including issues of potentially opposing resource objectives tied to flow treatments focused on sandbars, native fish and non-native trout. We suspect there are some very difficult trade-offs still to be fully confronted by Adaptive Management Program stakeholders with diverse values related to relict and artifact resources; including Glen Canyon National Recreation Area and Grand Canyon National Park managers with different objectives up and downstream of Lees Ferry. As the Adaptive Management Program now proceeds through the Long-Term Experimental and Management Plan environmental compliance process twenty years after the first environmental impact statement on Glen Canyon Dam, scientists will very likely continue to identify other important surprise learning opportunities. Managers must then decide whether or not to embrace such learning in their recommendations about future experimental and management designs for Glen Canyon Dam operation and long-term management of the Colorado River ecosystem.