Predicted Effects of a Spring Disturbance Flow on LTEMP Resources—a report by the FLow Ad Hoc Group (FLAHG) of the Glen Canyon Dam Adaptive Management Program

I. Background

Disturbance is a critical natural process in streams and rivers (Resh and others 1988, Poff and others 1997). By disrupting ecosystem structure and altering the availability of substrates and resources, flood disturbance helps maintain native biological diversity (Bunn and Arthington 2002, Carlisle and others 2017). Disturbance magnitude, for example the extent of drying at low flow or the proportion of the bed that is mobilized at high flows, can influence ecosystem outcomes by, for example, determining the extent of biomass loss and the quantity of newly scoured habitat patches available for recolonization by algae and aquatic insects (Lake 2000). Disturbance frequency and timing (e.g., spring vs. fall) can also influence the rate and trajectory of ecosystem recovery from disturbance (Figure 1 and Lytle and Poff 2004). The life cycles of many species of algae, insects and fish are directly tied to flood disturbances (Lytle and Poff 2004) and alterations to river flood regimes can adversely affect ecosystem health. In fact, a national synthesis of flow and biological data from over 700 streams and rivers in the lower 48 states found that healthy communities of native aquatic invertebrates and fish were most often present where flood disturbance still occurred, and where flood timing was seasonally appropriate (i.e., similar to the natural condition; Carlisle and others 2017). Although the Colorado River in Grand Canyon could not be included in this 2017 synthesis owing to the absence of pre-dam ecological data, the mechanisms linking periodic flow disturbance to stream ecosystem health were evaluated in a wide variety of streams and regions (Carlisle 2020). It is therefore reasonable to predict that similar mechanisms linking appropriately timed flow disturbance to ecosystem health also operate in the Colorado River.

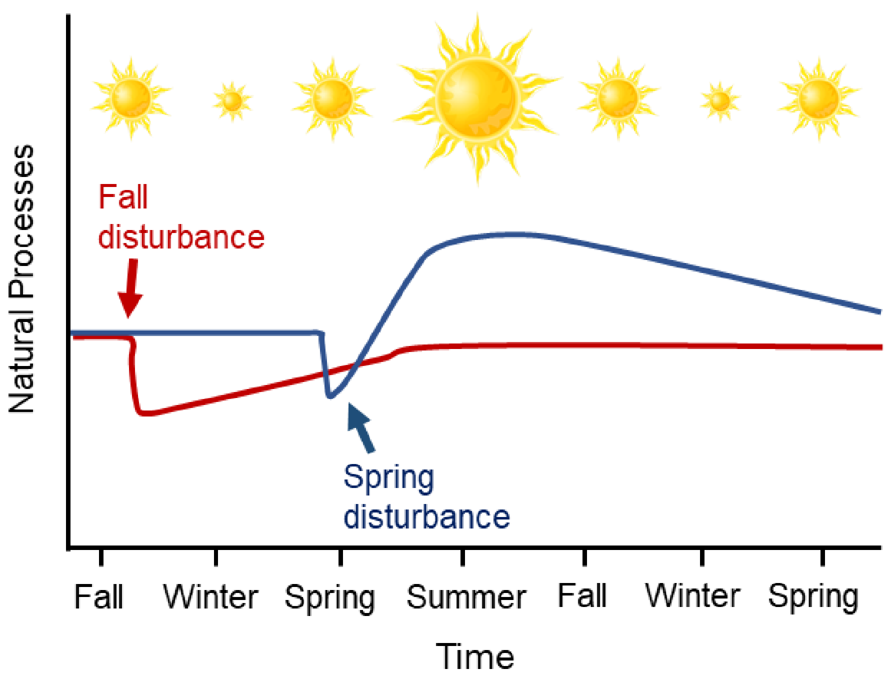

Figure 1. Conceptual figure showing the potential role of spring disturbance in enhancing natural processes (e.g., algae and aquatic insect production) of the Colorado River ecosystem.

The pre-dam Colorado River was characterized by spring snow-melt floods that often exceeded 100,000 ft^3/s and typically peaked in late June, followed by flash flood flows during the summer monsoon season, and extensive low base flows from the fall through early spring (Topping and others 2003). This seasonally variable flow regime was an important driver of natural processes in the CRe, and the unique fish species that evolved in the CRe were adapted to frequent flow disturbances (Minckley 1991). For example, the small eyes and tiny embedded scales that are common to several endemic fish are thought to be adaptations to the sediment laden floods that scoured the Grand Canyon annually.

Regulation of the Colorado River by Glen Canyon Dam in 1963 eliminated the annual spring high flow disturbances, increased base flow thereby eliminating periods of low flows, and substantially increased within day flow variation. In addition to changing the river's flow regime, Glen Canyon Dam also changed other aspects of the physical template, particularly temperature, sediment, and nutrient regimes (Wright and others 2009, Topping and others 2000, Yackulic and others 2018). These changes to the physical template of the river led to dramatic changes in its ecology. For example, river food webs are now primarily built upon algae production owing to clear water (Stevens and others 1997, Yard and others 2005, Cross and others 2013) whereas detritus and leaf litter are thought to have been primary sources of energy fueling pre-dam food webs (Blinn and Cole 1991, Haden and others 2003). Many species of non-native invertebrates (e.g., New Zealand mud snails, quagga mussels) and fish (e.g., rainbow trout, brown trout) are well-suited to this new physical template and have become established throughout the Grand Canyon segment. In spite of these changes to the ecosystem and the processes that support its food webs, native fish populations in Grand Canyon are stable and relatively robust compared to other segments of the Colorado River (Yackulic and others 2014, Healy and others 2020, Dibble and others *in review*).

The 2016 Long-Term Experimental and Management Plan (LTEMP) seeks to enhance key resources through testing of both flow and non-flow actions. High Flow Experiments (HFEs) are the principal type of flow disturbance evaluated as part of LTEMP. The sediment accounting approach to triggering HFEs used in the 2016 LTEMP was actually developed earlier, in 2011 (U.S. Bureau of Reclamation 2011). The 2011 HFE protocol was based upon insights from testing HFEs in March/April 1996, November 2004, and March 2008 (Webb and others 1999, Melis 2011). These early HFEs indicated that natural processes and other biological resources would be maximized with spring timing (Webb and others 1999, Wright and Kennedy 2011) while retention of fine sediment above the elevation of average base flow would be maximized with fall timing (Schmidt and Grams 2011, Wright and Kennedy 2011). At the time the HFE protocol was developed, it was unclear whether fish or natural processes would be affected by fall timed HFEs, because there was minimal biological monitoring during the 2004 fall HFE (Kennedy and Ralston 2011).

The 2008 spring HFE was particularly well studied and appeared to enhance natural processes (Cross and others, 2013) and also built extensive new sand bars (Schmidt and Grams 2011), both of which are consistent with program goals. However, the 2008 spring HFE was also associated with an 800 percent increase in relative abundance of non-native rainbow trout near the Little Colorado River confluence, which was inconsistent with program goals (Kennedy and Ralston 2011). Because these resource responses and potential tradeoffs associated with spring vs. fall HFEs were highly uncertain, even for sediment, the HFE protocol was designed to reduce these uncertainties through regular testing of both spring and fall HFEs (Wright and Kennedy 2011).

To test both spring and fall HFEs, the HFE protocol proposed using two sediment accounting periods. These sediment accounting periods are used to track the quantity of new Paria River sand available for building beaches in Marble Canyon during an HFE, and HFEs are only triggered if the quantity of new sand is large. This sediment accounting approach to triggering HFEs, coupled with state-of-the-art sediment monitoring (Topping and Wright 2016), eliminates the possibility of unintentionally scouring sediment resources from Marble Canyon during HFEs. When the HFE protocol was first proposed, it was estimated that sediment-triggered fall HFEs would occur approximately two out of every three years and sediment-triggered spring HFEs would occur approximately once every three years (Wright and Kennedy 2011).

The 2016 LTEMP-EIS adopted this same sediment accounting framework for triggering fall and spring HFEs, but LTEMP also created additional flexibility for testing HFEs beyond what was described in the 2011 protocol. For example, LTEMP included a new provision for extended duration fall HFEs up to 250 hours long instead of just 96 hours, because of insights from the highly sediment-enriched fall HFE in 2013. LTEMP also created an opportunity for Proactive Spring HFEs, which are not tied to a sediment trigger and can occur across a wider range of months (April, May, or June) than the original protocol allowed (March or April only). Compliance associated with both the 2011 HFE protocol and the 2016 LTEMP also included prohibitions on testing spring HFEs to avoid the possibility that they would inadvertently increase rainbow trout abundance at the Little Colorado River confluence to the detriment of endangered humpback chub. These prohibitions on spring HFEs were in place from 2012-2019.

Although Sediment-Triggered Spring HFEs and Proactive Spring HFEs are now possible, analysis of Paria River discharge data indicates that Sediment-Triggered Spring HFEs may occur less frequently than originally estimated (Grams and Topping 2018). Sediment accounting data available since the HFE protocol was operationalized in 2012 bear this out. Specifically, since 2012 the sediment trigger for a fall HFE has been reached 6 times (i.e., 2012-2016, 2018; no HFE occurred in 2015 owing to green sunfish) while the sediment trigger for a spring HFE has never been reached (Grams and Topping 2020). Testing of 5 fall HFEs over the past 8 years has benefitted sediment resources and reduced uncertainties concerning sandbar response to HFEs in general (Figure 2). However, regular testing of fall HFEs since 2012 is also correlated with a growing population of brown trout in Lees Ferry (Runge and others 2018) and critical uncertainties concerning the role of spring HFEs in achieving biological resource objectives remain unanswered (Figure 2).

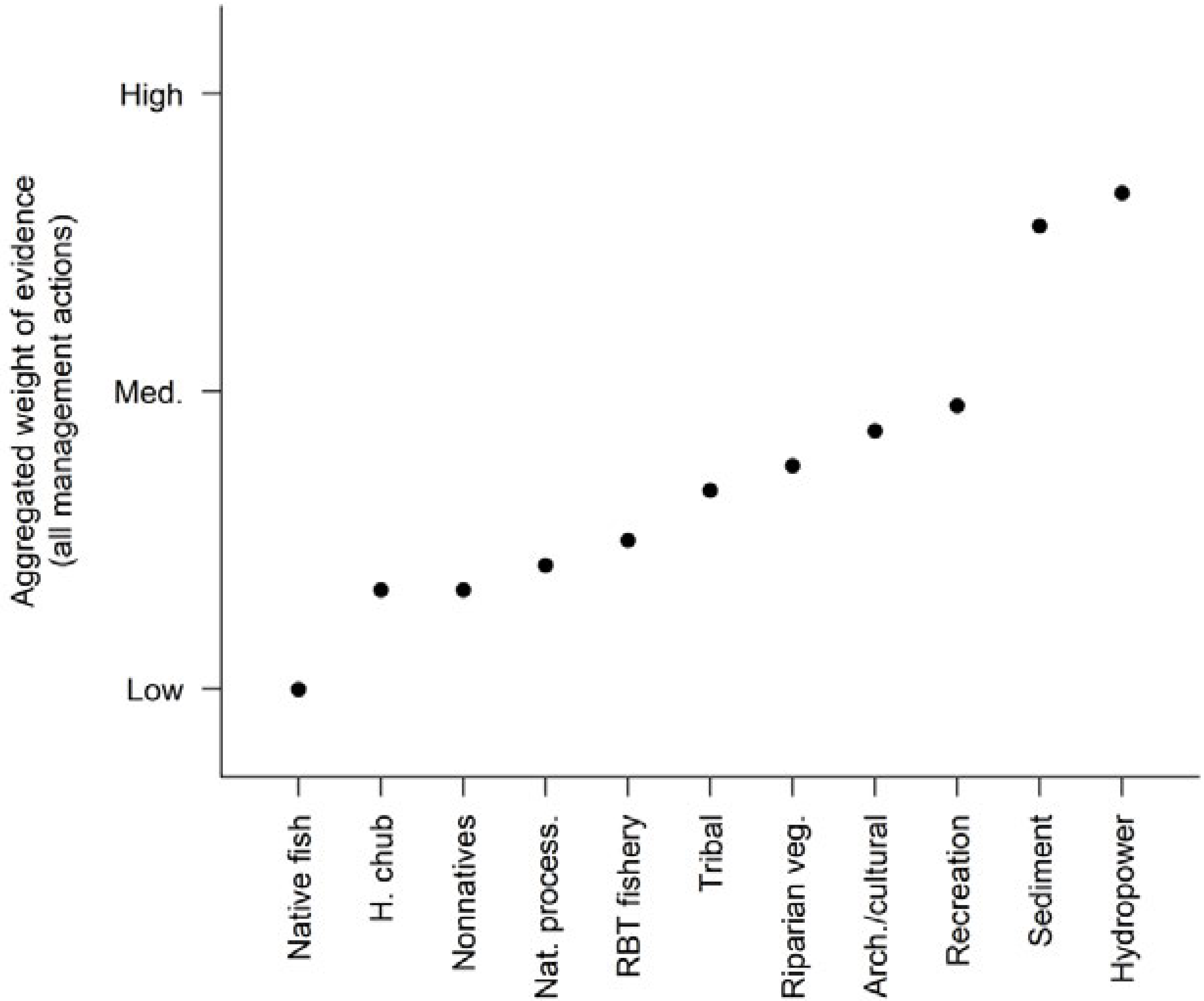

Figure 2. LTEMP goals associated with fish and aquatics (left side of graph) have some of the highest levels of critical uncertainty (i.e., lowest weight of evidence) concerning the role of flow disturbance timing in achieving program objectives. Points represent the average weight of evidence from the 2020 Knowledge Assessment aggregated across the 3 management actions that were considered (i.e., FLAHG hydrograph, Spring HFE, Fall HFE). Goal ordering along x-axis is from lowest-to-highest weight of evidence. See section III. below for details of the 2020 Knowledge Assessment.

II. A Path Forward

To explore options for spring disturbance flows that will help reduce these uncertainties, the Flow Ad Hoc Group (FLAHG) was formed and in December 2019 they were charged with:

> *…working with GCMRC to evaluate opportunities for conducting higher spring releases that may benefit high value resources of concern to the GCDAMP (recreational beaches, aquatic food base, rainbow trout fishery, hydropower, humpback chub and other native fish, cultural resources, and vegetation), fill critical data gaps, and reduce scientific uncertainties.*
>
> *As a starting point, the FLAHG shall consider the benefits of and opportunities for conducting higher spring releases within power plant capacity.*

By May 2020, the FLAHG and GCMRC completed design of a conceptual hydrograph that included a high spring release that was within power plant capacity. The FLAHG hydrograph capitalizes on a unique low flow of 4,000 ft^3/s for 5 days, which is needed to conduct maintenance on the apron of Glen Canyon Dam (see Figure 3). The FLAHG hydrograph proposes to follow this low flow disturbance with a high flow disturbance that will culminate in a discharge of up to 25,000 ft^3/s for 82 hours. This combination of desiccation at low flows followed by scour at high flows is hypothesized to disturb benthic habitats to a much greater extent than either the low or high flows alone (Kennedy and others 2020).

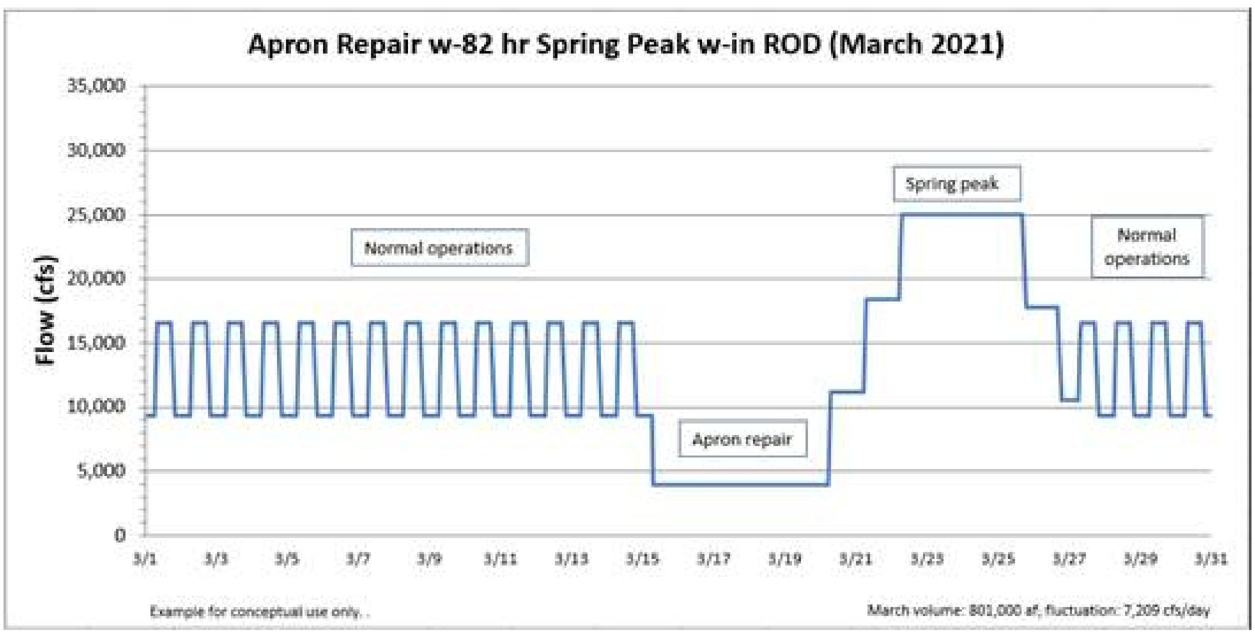

Figure 3. Conceptual hydrograph developed by the FLAHG that was evaluated in this document.

III. Knowledge Assessment

Below we present predicted effects of the FLAHG hydrograph on the 11 LTEMP Resource Goals using the Knowledge Assessment rubric from 2019 (http://gcdamp.com/index.php?title=Portal:GCDAMP_Knowlege_Assessments). For comparison, and to anchor predictions concerning the FLAHG hydrograph, we also used the Knowledge Assessment framework to predict effects of Spring and Fall HFEs on LTEMP Resource Goals. To simplify analysis of hydrograph impacts, the FLAHG narrowed consideration of testing this hydrograph to sometime in March based on the following two main reasons: 1) both the 1996 and 2008 Spring HFEs also occurred in March, which will simplify evaluation and comparison of new biological data that might be collected around a FLAHG hydrograph to earlier data from those spring HFEs, and 2) a March test of the FLAHG hydrograph will minimize adverse impacts of the low flow to Recreational Experience by avoiding the start of the commercial river trip motor season in April.

Knowledge Assessment groups often evaluated multiple specific measures to capture all the facets of a given LTEMP goal. For example, the goal for Rainbow Trout Fishery is, “Achieve a healthy high-quality recreational rainbow trout fishery in GCNRA and reduce or eliminate downstream trout migration consistent with NPS fish management and ESA compliance.” To capture both facets of this goal, the Knowledge Assessment team considered two specific measures: rainbow trout abundance in Lees Ferry, and rainbow trout abundance at the Little Colorado River confluence. The predicted resource responses to a given action often varied, depending on which specific measure was considered. We capture this variation in predictions by presenting bookend, “lowest performing” and “highest performing”, scenarios gleaned from the assessments and their differing specific measures. Note that the assessment summaries and graphs are based on detailed assessments for each resource that were performed by multiple subject matter experts (see section V. Acknowledgements for a complete list of participants). Those detailed assessments are contained in a spreadsheet for each resource that accompany this document. The detailed resource assessments were based on consideration of peer-reviewed literature, modelling, and other quantitative science as well as more qualitative expert opinions, similar to previous Knowledge Assessments.

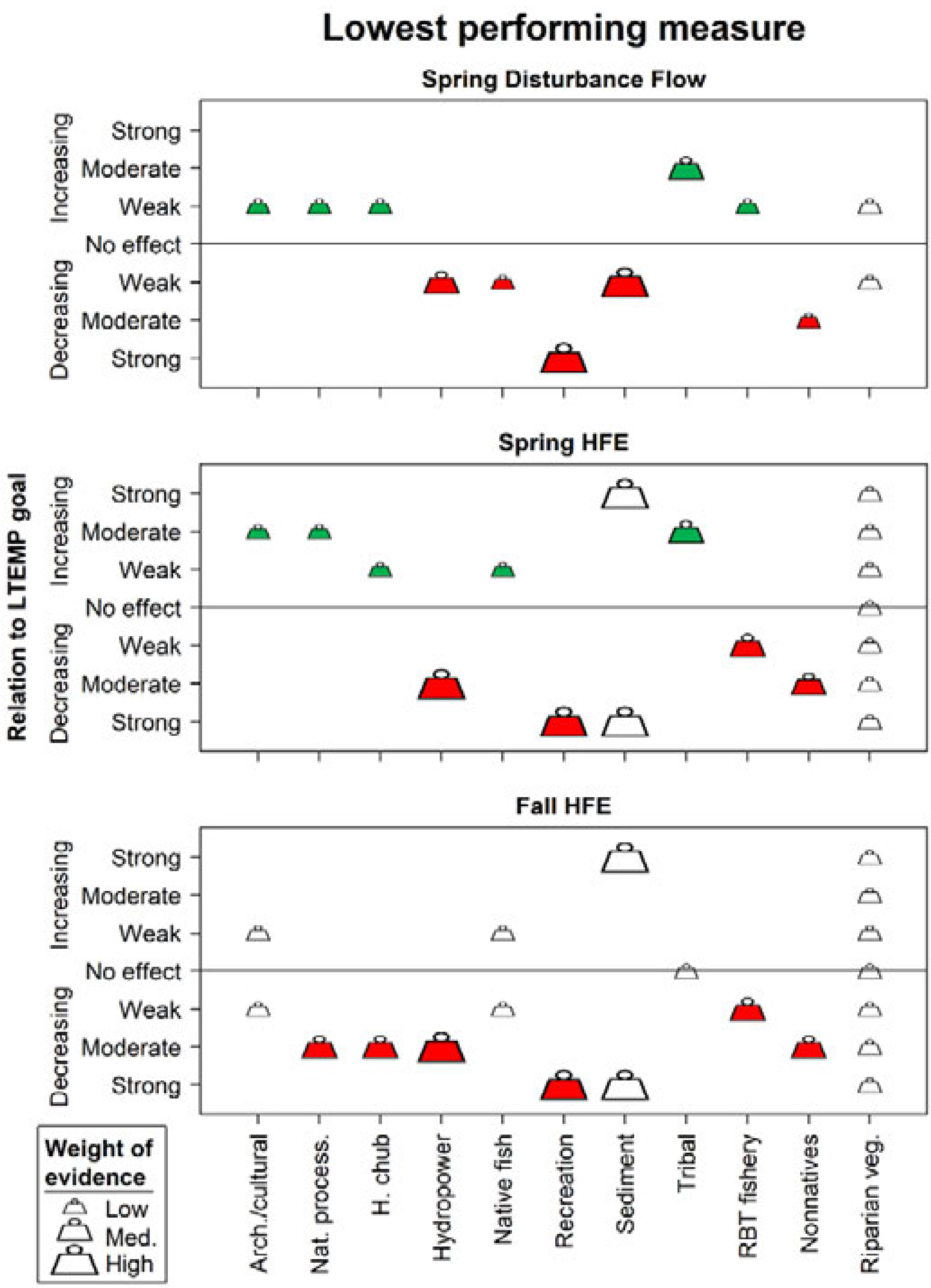

Figure 4. Graph showing the lowest predicted effects of a Spring Disturbance Flow (i.e., FLAHG hydrograph), a Spring HFE, and a Fall HFE on LTEMP resources. Open symbols indicate resources where the direction of effect and/or the strength of the effect was unknown. Low weight of evidence indicates greater levels of critical uncertainty whereas high weight of evidence indicates lower levels of critical uncertainty. For information about the Knowledge Assessment rubric, navigate to *http://gcdamp.com/index.php?title=Portal:GCDAMP_Knowlege_Assessments*

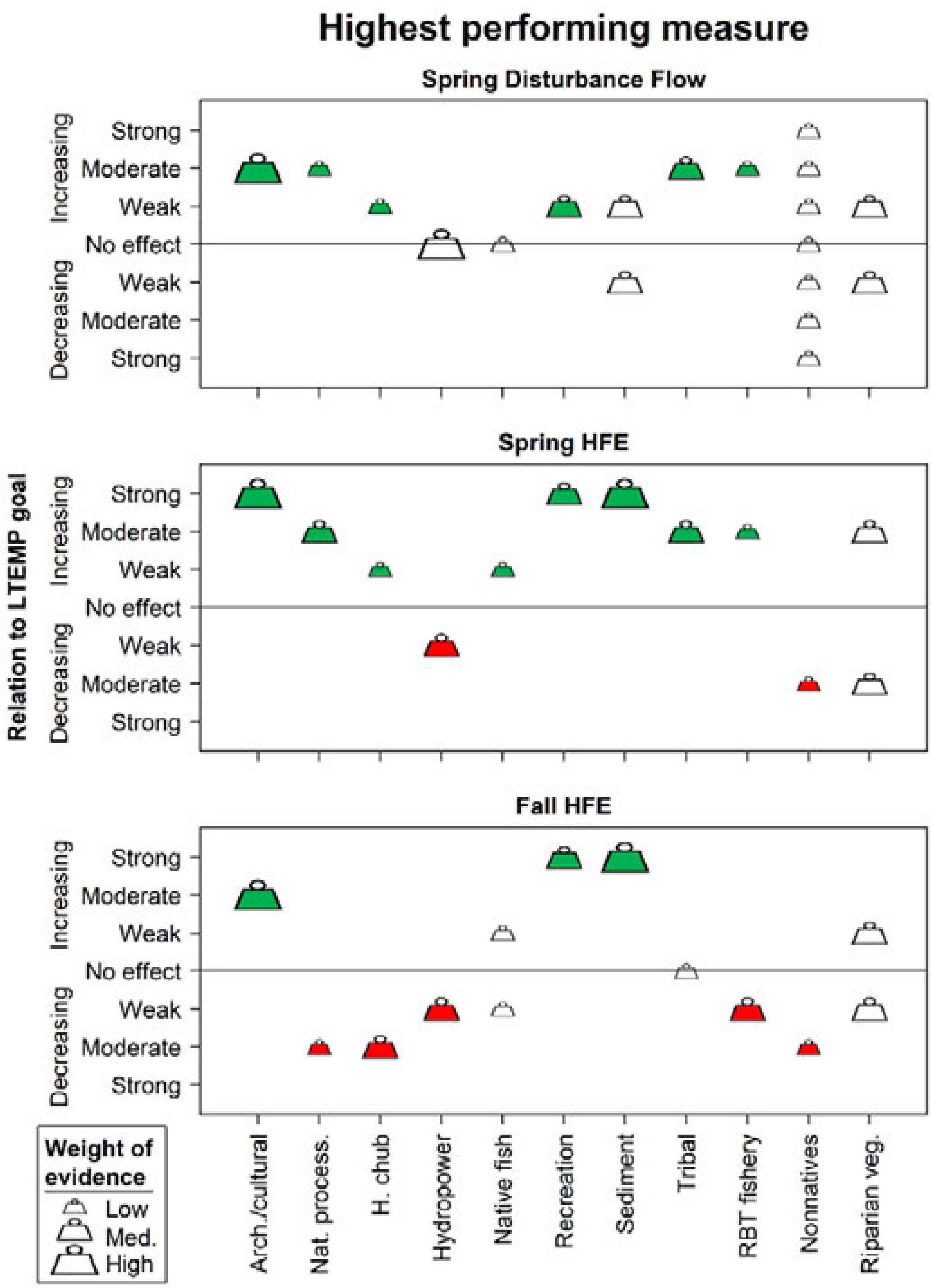

Figure 5. Graph showing the highest predicted effects of a Spring Disturbance Flow (i.e., FLAHG hydrograph), a Spring HFE, and a Fall HFE on LTEMP resources. Open symbols indicate resources where the direction of effect and/or the strength of the effect was unknown. Low weight of evidence indicates greater levels of critical uncertainty whereas high weight of evidence indicates lower levels of critical uncertainty. For information about the Knowledge Assessment rubric, navigate to http://gcdamp.com/index.php?title=Portal:GCDAMP_Knowlege_Assessments

IV. Qualitative Narratives

Below are qualitative narratives describing predicted effects of the FLAHG hydrograph on the 11 LTEMP Resource Goals. Note that these qualitative narratives are for a single test of the FLAHG hydrograph sometime in the month of March and in the context of current resource conditions (i.e., 2020). These narratives are intended to add nuance and detail to the Knowledge Assessment analyses, and the reader is encouraged to refer back to Knowledge Assessment graphs if the meaning or implications of these narratives is unclear.

Archaeological and Cultural Resources

No major impacts to archaeological or cultural resources are anticipated if the FLAHG hydrograph is implemented. The FLAHG hydrograph nonetheless represents a valuable opportunity to understand how spring disturbance flows affect archaeological and cultural resources.

For cultural resources other than archaeological sites, such as traditional cultural places (TCPs), the predicted effects from the FLAHG hydrograph are expected to be minor, considering that the upper limit of the hydrograph is still within normal dam operations. However, considering that these kinds of resources encompass a wide variety of TCPs, which include ancestral archaeological sites but may also include springs, landforms, shrines, plant and mineral gathering areas, and many others, the actual effects may vary widely, as well. It must be understood that the different participant tribes in the GCDAMP do not necessarily view these places from the same perspective, and the way that effects are ultimately perceived may vary as well. It also must be pointed out that the distinction of “Archaeological and Cultural Resources” from “Tribal Resources” does not mesh well with the perspectives of the tribal stakeholders in the GCDAMP, who view all of these as an inextricably intertwined whole and the entire landscape within the Colorado River ecosystem as a holistic and sentient entity.

The low flow portion of the hydrograph may temporarily increase aeolian transport of sand from the river channel to archaeological sites in dunefields by increasing the amount of exposed sand available for aeolian transport by as much as 400% (Kasprak and others in review, Kasparak and others 2018, Sankey and others 2018). However, the duration of the low flow is short and so effects on aeolian transport are expected to be minor. Although the high flow portion of the hydrograph will decrease the supply of sand available for aeolian transport, the duration of high flows is also short, so any reductions in aeolian transport are expected to be temporary and minor.

Natural Processes

For the purposes of this document, we evaluate how the FLAHG hydrograph will affect two key natural processes (algae production, insect production), which were identified by GCMRC scientists as representative of the LTEMP goal. Although algae production may not have historically been an important natural process sustaining river food webs (Kennedy and others 2013), in the post-dam river algae constitutes the base of the food web in Glen, Marble, and Grand Canyon (Stevens and others 1997, Cross and others 2013). Continuous monitoring of algae production at multiple sites using dissolved oxygen sensors began in 2011 and has allowed scientists to estimate GPP on daily time scales (Hall and others 2015). Aquatic insects are the primary prey consumed by native and desired non-native fishes in the post-dam river (Kennedy and others 2013) and insects are also thought to have represented a cornerstone of pre-dam food webs (Kennedy and others 2016). Monitoring insect production in the drift has occurred continuously since 2008 (Kennedy and others 2014) and using citizen science light trapping since 2012 (Kennedy and others 2016).

The FLAHG hydrograph will likely alter rates of algae production (technically, gross primary productivity, or GPP) and these effects will vary by river segment. In the Glen Canyon segment, the FLAHG hydrograph should lower overall GPP owing to desiccation and scour of rooted aquatic vegetation during the low and high flow portions of the hydrograph, respectively. Although total GPP is expected to be lower in Glen Canyon, the availability of newly cleaned gravel substrates is expected to increase production of fast-growing and palatable diatoms, which should in turn lead to increased production of aquatic insects (Project O.1), similar to what was documented during the 2008 HFE (Cross and others 2011).

In Grand Canyon, cobble bars and shallow edge habitats are hot-spots for GPP and insect production, and deeper pools are generally unproductive (Stevens and others 1997, Cross and others 2013, Hall and others 2015). The FLAHG hydrograph is expected to desiccate and scour cobble bars and other edge habitats, leading to declines in GPP over the short term. This disturbance is predicted to also favor fast growing and palatable diatoms, and disadvantage the unpalatable blue-green algae (i.e., *Oscillatoria* spp.) that can sometimes proliferate in the intertidal zone in Grand Canyon (Stevens and others 1997). Blue-green algae do not fuel invertebrate growth (Stevens and others 1997, Wellard-Kelly and others 2014), so this predicted shift in composition of primary producers towards palatable diatoms is expected to increase insect production over the long-term (see Project O.1). For aquatic insects, black flies may show a particularly strong positive response to the FLAHG hydrograph owing to improvements in habitat quality associated with scouring cobbles and cleaning substrates; black fly densities are greatest on clean cobble bars and they exhibited a nearly 400% increase in production following the 2008 spring HFE (Cross and others 2011).

Phosphorus concentrations may be an important modifier of ecosystem responses to the FLAHG hydrograph. The FLAHG hydrograph has the potential to increase phosphorus concentrations over the short-term owing to desiccation and subsequent mineralization of organically bound phosphorus during low flow, followed by phosphorus release during the high flow. This phenomenon of phosphorus release immediately following drying and desiccation of edge habitats has been documented across diverse sediment types (Kinsman-Costello and others 2016). Whether this pulse of phosphorus occurs during a FLAHG hydrograph test may depend on overall background sediment P concentrations in the varial zone. If phosphorous concentrations are elevated during the FLAHG hydrograph test, either because of the mechanisms described above or owing to high phosphorus releases from the dam, this would also be expected to favor fast-growing diatoms during the recovery phase that follows a disturbance. Turbidity during the months following the FLAHG hydrograph will also be an important modifier of ecosystem response, with low turbidity conditions expected to favor fast-growing diatom and insect production while elevated turbidity conditions may slow these processes.

Humpback Chub

No major impacts to humpback chub are anticipated if the FLAHG hydrograph is tested. The low and high flows of the FLAHG hydrograph, while unusual relative to base dam operations, are minor compared to the extreme low and high flows the river historically experienced. Thus, humpback chub are unlikely to be stranded at low flows or displaced at high flows during testing of the FLAHG hydrograph. Any effects of the FLAHG hydrograph on humpback chub would likely be through indirect impacts on GPP and/or the invertebrate prey base given the proposed timing of the action in early spring. The likelihood of any such impacts affecting humpback chub growth rates is highly uncertain, however, because there have been no spring HFEs or other spring-timed disturbances in the >10 years since rigorous mainstem monitoring of humpback chub began with the Near-Shore Ecology Project in 2009. Repeated testing of spring high flows could potentially synchronize humpback chub spawning in western Grand Canyon, where mainstem spawning is thought to have occurred, leading to higher overall juvenile humpback chub production at that location. However, because water temperatures in early spring are likely to be too cold for mainstem spawning, and it is unclear where humpback chub mainstem spawning is even occurring, the likelihood of such a synchronization response to a single spring disturbance is also highly uncertain. Project O.7 proposes to study movement of humpback chub in response to the FLAHG hydrograph, which may help reduce these uncertainties concerning the role that flow and temperatures cues play in driving spawning and movements.

Hydropower and Energy

This hydropower analysis evaluates the impact of re-programming releases to accommodate a possible apron repair proposed for March 2021 using the hourly market prices to value the electrical energy produced by Glen Canyon Dam. The baseline case for this analysis includes five days of reduced releases for apron repair. Comparisons are made in how to reprogram the water that would have been released during the apron repair while staying within the scheduled monthly volume for March 2021.

Two release scenarios were evaluated with one rescheduling the water across the remaining month of normal operations and the other rescheduling the water to be released as a block for a spring peak. To illustrate, Figure 6 shows a simplified release pattern for a 9.0 MAF March volume as described in LTEMP. Figure 7 shows that same simplified release pattern adjusted to accommodate the proposed apron repair. Note in Figure 7 how the monthly hydrograph has been adjusted to accommodate the week-long apron repair by increasing the base and peak flows in order to utilize the water that was not released during the apron repair while still staying within the daily flow fluctuation limits prescribed in LTEMP. This hydropower analysis compares the hydrograph with the apron repair as presented in Figure 7 with the proposed FLAHG hydrograph as presented in Figure 3.

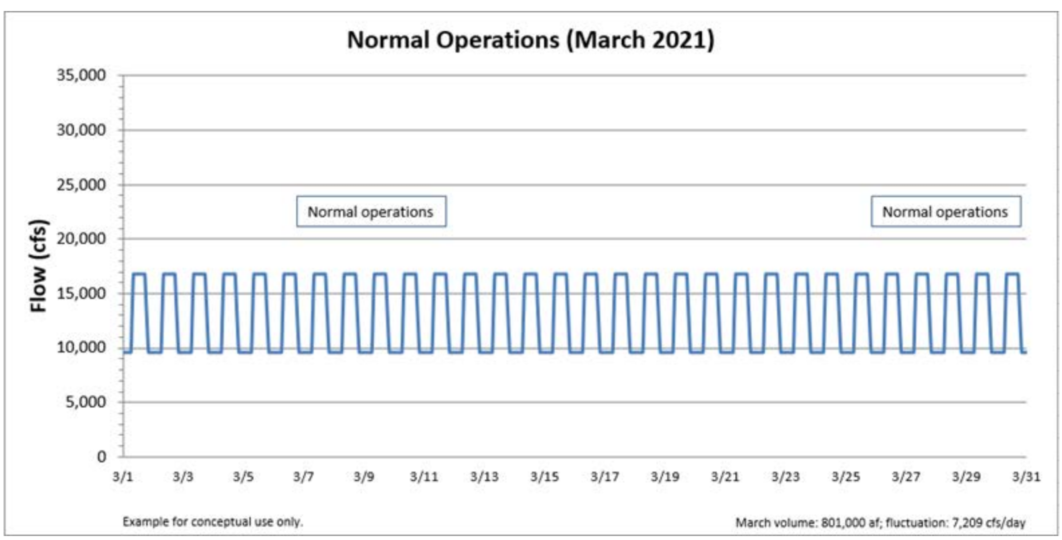

Figure 6. A simplified release pattern for a 9.0 MAF March volume as described in LTEMP.

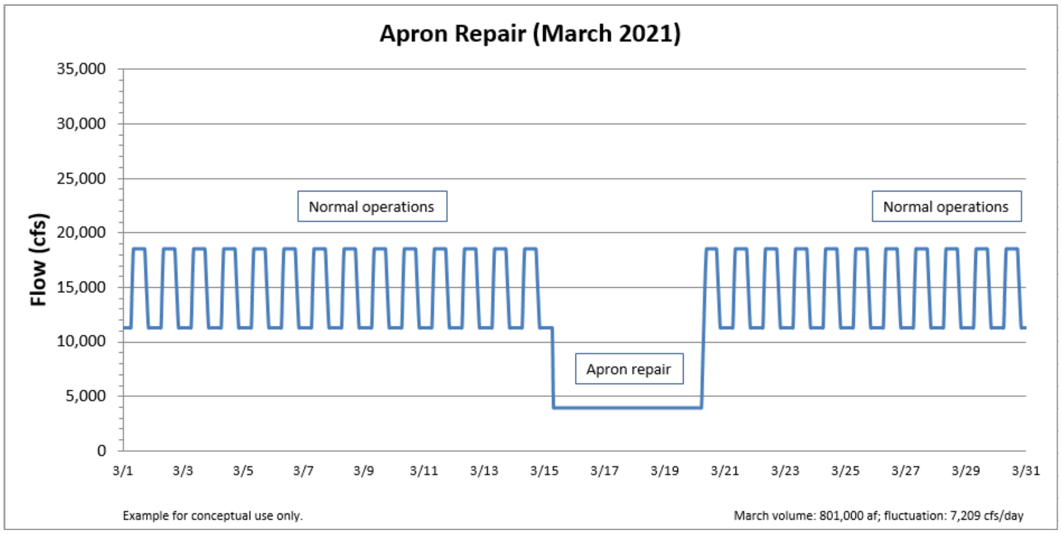

Figure 7. A simplified release pattern for a 9.0 MAF March volume as described in LTEMP adjusted to accommodate the proposed apron repair.

The evaluation of the hydropower impacts of the apron repair and rescheduling water to either the rest of the month or as a block release for a spring peak shows very little impact to hydropower. This is primarily due to a low differential in on-peak and off-peak power prices that are typical for shoulder power months. Redistributing water from the apron repair to a spring peak yielded small decreases in energy value when compared to redistributing water from the apron repair into normal operations over the remainder of the month. Finally, as a sensitivity analysis, we also evaluated a range of spring peak durations (i.e., 34, 58, 82, and 106 hours) to evaluate how duration of the spring peak affected hydropower, and overall impacts to hydropower remained small across all these duration scenarios.

Other Native Fish Species

The LTEMP goal for Other Native Fish Species refers to razorback sucker, flannelmouth sucker, bluehead sucker, and speckled dace, however this assessment of potential impacts was limited to species of conservation concern (sucker species, either ESA-listed or subject of interagency conservation strategies). No major direct impacts to Other Native Fish Species are anticipated if the FLAHG hydrograph is tested. As described above for humpback chub, the overall range of flows being tested in the FLAHG hydrograph is relatively minor compared to pre-dam flow regimes under which native fish evolved, so direct effects of stranding and downstream displacement are unlikely. Nonetheless, there is a slight chance the low flows associated with the FLAHG hydrograph could desiccate spawning habitat or incubating eggs of razorback sucker, particularly if the flow occurs in mid-March. Back-calculations from larval razorback sucker collected in 2014 and 2015 indicate peak spawning occurred in mid-March in those years (Gilbert and others *in review*). Literature suggests razorback sucker spawning may occur on cobble bars that are susceptible to low flows, however spawning locations and habitat in Grand Canyon are unknown. Given low larval catch rates of razorback sucker in recent years, and lack of detection of adults or movements of adults out of Lake Mead into Grand Canyon, likely few remain.

Spring high flows could stimulate the food base for other native fish species in Grand Canyon, leading to higher overall juvenile native fish production, although effects may be damped in western Grand Canyon, similar to what was observed in the 2008 spring HFE (a single replicate; Cross and others 2013).

However indirect negative effects could occur through predation or competition if rainbow trout production increases (see Rainbow Trout Fishery section). FLAHG low flows followed by a high spring pulse may discourage production of brown trout, which could indirectly benefit native fish in Grand Canyon, if we assume downstream migration from Glen Canyon is density-dependent. Literature suggests similar flows during critical incubation and emergence periods, through loss of habitat or through reduced feeding opportunities for newly emerged brown trout fry, could limit brown trout recruitment (e.g., Lobón-Cerviá 2009). Minimizing brown trout abundance in Grand Canyon may contribute to the maintenance of other native fishes (Healy and others 2020), but the variation in flow associated with the FLAHG hydrograph may be of insufficient magnitude to impact brown trout reproduction. To reduce these uncertainties, Projects O.1 and O.6 of the FY21-23 workplan proposes to study the response of food webs and brown trout early life stage impacts related to the FLAHG hydrograph.

Recreational Experience

The FLAHG hydrograph represents an important opportunity to test whether high flows in spring improve navigation in western Grand Canyon immediately prior to the high use boating season (see Project O.2). Poor navigation has been identified as an issue of concern by the Hualapai Tribe for many years, as the Tribe operates a river running enterprise in this reach of the river. Navigation risk in this reach impacts recreation resources for the Tribe and other non-tribal river recreation. Both tribal and non-tribal river trips have noted safety concerns due to sandbars just below the surface. If the FLAHG hydrograph is capable of opening a more reliable navigation channel, even if only temporary or seasonal, this may help alleviate some of these concerns.

No major adverse impacts to recreational experience are anticipated if the FLAHG hydrograph is implemented based on the limited duration of the action. However, minor impacts to recreational experience are expected and vary by recreation type. No impact is anticipated for river corridor access. For flatwater boating in the Glen Canyon reach, the FLAHG hydrograph is anticipated to have no impact. This is based on the Bishop and others (1987) finding that flow has no significant impact on flatwater boating in Glen Canyon. For whitewater boating, the FLAHG hydrograph is anticipated to negatively impact navigation and time on river during the five days of low flow and increase the risk of wrapping or stranding boats. The maximum discharge of the FLAHG hydrograph will benefit whitewater boating. Whitewater boaters have strong preferences for flows of this magnitude and discharges will be similar to those during summer months (Bishop and others 1987, Neher and others 2017). The action is not expected to increase sediment deposition, but the low flow will increase camp-able area temporarily and the pulse flow may ‘refresh’ camps that have been disturbed by gully erosion and other factors.

It is anticipated that the low flow of the FLAHG hydrograph will have a strong negative effect on angler access in Glen Canyon, creating navigational risks, although fishing may improve as low flows reduce drift and may enhance the attractiveness of artificial lures. These effects, either positive or negative, will be of limited duration. Also, steady flows of 4,000 ft^3/s are not as preferred as flows in the 10,000 to 25,000 range (Bishop and others 1987, Duffield and others 2016). However, estimates of angler preferences for low steady flows lacks precision (Duffield and others 2016). Outside of the immediate timeframe of the action, rainbow trout abundance and condition are expected to increase. Although the FLAHG hydrograph is not expected to result in a significant impacts on the recreational experience, the FLAHG hydrograph represents an important opportunity to test whether low steady flows have a significant impacts on navigational risk and the angling experience in Glen Canyon, in anticipation of potential future experiments with similar hydrographs (see Project O.8).

Sediment

No major impacts to sandbar resources are anticipated if the FLAHG hydrograph is implemented. The five days of low flows may result in cutbank formation on some sandbars, but will decrease the background export of sand from eddies, changes that will be offset by higher than normal erosion during the high flow portion of the hydrograph. Because the maximum discharge of the spring hydrograph is only 20,000-25,000 ft^3/s, which is just slightly higher than normal peak discharges during winter and summer months, and the 82 hours at peak discharge is relatively short, the FLAHG hydrograph is expected to have weak impacts on sandbar volume, sand storage, and campsite area. Sandbar volume and campsite area could have small increases, small decreases, or could remain unchanged. The direction of the response is uncertain, because some bars are likely to increase and some erode, while the overall magnitude of effect is predicted to be weak. Antecedent operations, such as the ~20,000 ft^3/s "power emergency" releases that have occurred in 2020 and whether or not an HFE occurs in fall 2020 will determine sediment supply and concentration during the FLAHG hydrograph test, which will in turn affect sandbar response. For example, some campsites may benefit from small amounts of deposition that may not substantially change sandbar area, but will likely fill and smooth out minor features such as gullies, which improves campsite condition. Low-elevation sand storage in eddies overall is expected to decrease, because the 20,000-25,000 ft^3/s pulse will increase the rate of sand transport. However, the impact that elevated sand transport has on sand storage will likely vary by river segment, and some segments may experience zero net change or increasing sand storage during the FLAHG hydrograph test.

Tribal Resources

The LTEMP FEIS considers Tribal Resources as two intertwined domains: “(1) traditional cultural places (TCPs)—those elements with fixed and defined locations, and (2) traditional cultural resources—resources that are either widely scattered or mobile, such as riparian vegetation, birds, mammals, and fishes” (FEIS 4-251). The latter domain essentially falls within the general category of the river corridor’s ecosystem, as measured by the health of the ecosystem, as well as the health of the river’s spiritual nature. It must be pointed out that the distinction of “Tribal Resources” from “Archaeological and Cultural Resources” does not mesh well with the perspectives of the tribal stakeholders in the GCDAMP, who view all of these as an inextricably intertwined whole and the entire landscape within the Colorado River ecosystem as a holistic and sentient entity.

As the proposed upper end of the FLAHG hydrograph is within normal dam operations, it is not expected to result in any additional direct impacts to archaeological sites or TCPs that would not occur under these normal conditions. Although sediment transport and sandbar building is expected to be relatively minimal compared to HFEs, some sediment could be deposited on lower beach and bank areas near ancestral archaeological sites and temporarily stabilize or enhance existing conditions, with some sand redepositing through aeolian transport further upslope, potentially providing sediment for covering certain archaeological sites in optimal locations. However, as the kinds of TCPs varies widely and their significance to the various participant tribes in the GCDAMP varies as well, the specific predicted impacts are difficult to predict without further observations by tribal monitoring trips.

As discussed previously, it is expected that high flow releases in the spring, even though very limited in comparison to pre-dam conditions, would more closely emulate pre-dam natural flow regimes, resulting in responses by plant and animal communities along the river that are predicted to enhance the ecosystem by promoting spring reproductive and growth patterns that existed before the dam to some extent. In this regard, the proposed hydrograph may have the potential to "increase the health of the ecosystem in Glen, Marble, and Grand Canyons (see Tribal Resource Goal 4.9.1.1 in the FEIS; also Philips and Jackson 1997, Dongoske and Seowtewa 2011, Joe 2014, Bullets 2015, Yeatts 2018). This would be expected to be true for both plant and animal species, and aquatic and riparian species in particular. Direct evidence of the important role of spring high flows in enhancing health of the Colorado River ecosystem is seen in annual trends in frog populations, which appear to have increased in years with high spring flows (Larry Stevens, personal communication to Peter Bungart).

Rainbow Trout Fishery

The FLAHG hydrograph has the potential to moderately positively affect the rainbow trout fishery in Lees Ferry, but the strength of that effect will likely depend on the response of the food base to the proposed flow. The low flow associated with apron repair work will dewater approximately 20-25% of the channel Glen Canyon-wide and up to ~50% of the bars closest to the dam relative to typical maximum flows in March (Kennedy and others 2020). This dewatering has the potential to kill emerging rooted macrophytes or macroalgae (e.g., Benenati and others 1998), dependent on the degree to which atmospheric conditions and solar radiation heat littoral edge habitat. We anticipate the subsequent scour and cleaning of cobble will facilitate re-growth of diatom assemblages that are more palatable to invertebrate consumers, such as *Gammarus lacustris*, Simuliidae, and Chironomidae, similar to what occurred in Spring 1996 and 2008 after those HFEs (e.g., Webb and others 1999; Cross and others 2013; Korman and others 2011). The proportion of invertebrate production attributable to diatoms was roughly equivalent in the years prior to and after the 2008 spring HFE, and invertebrate production declined by about half following the flood. However, high-quality invertebrate prey supported by diatoms increased in the drift following the spring HFE, and those items were consumed at a higher rate by age-0 and 1 rainbow trout, thus increasing rainbow trout production (Cross and others 2011, 2013). Further, the FLAHG hydrograph might improve the quality of spawning gravels for rainbow trout through scour of fine sediment and improve the rearing and feeding environment for juvenile rainbow trout that emerge 2 months or more after the flow, similar to what was observed in spring 2008 (e.g., Korman and others 2011).

There is a high degree of uncertainty related to the effects of the FLAHG hydrograph on rainbow trout near the LCR. This hydrograph has the potential to disadvantage rainbow trout through its effects on primary production at the base of the food web near the LCR. Due to the stage-discharge relationship and the narrow channel near the LCR, these effects will manifest primarily through the low flow associated with apron repair work and desiccation of edge habitat. Aquatic vegetation along the edge may slough off, and it is unclear how quickly *Cladophora*, *Oscillatoria*, diatoms, and other algae will re-colonize in early spring at cold temperatures. While the food web downstream from the LCR exhibited high resistance to the spring HFE in 2008, likely owing to relatively high food web complexity (Cross and others 2013), the dewatering associated with the FLAHG hydrograph represents a disturbance that could have longer-lasting effects near the LCR. In addition, there is the potential for increased interactions between rainbow trout and humpback chub during the low flow associated with apron repair work, since fish will be concentrated into a smaller area. However, the outcome of those interactions is complex and depends on turbidity levels in the water, as increased clarity will temporarily lead to better conditions for visual sight-feeding trout. We anticipate these potential negative interactions will abate with the return to higher discharge levels and the de-concentration of fish populations during the pulse flow.

Nonnative Invasive Species

No major impacts to Nonnative Invasive Species are anticipated if the FLAHG hydrograph is tested. Green sunfish may take advantage of the high flow portion of the FLAHG hydrograph and colonize areas like the -12 mile slough, but this colonization would likely be facilitated later in the summer anyway, when summer peaking flows will be similar to the FLAHG peak discharge.

The FLAHG hydrograph may disadvantage Brown Trout owing to reduced survival of emerging fry. High flows in late winter or early spring are known to disadvantage Brown Trout, because this timing coincides with the period of fry emergence, when young fish are searching out territories and feeding positions (Runge and others 2018 and references therein). Thus, the high flow portion of the hydrograph may displace brown trout fry and lower their survival. It is possible that the low flow portion of the FLAHG hydrograph may strand some brown trout fry, however, the downramp rate (2,500 ft^3/hr) of the hydrograph is within LTEMP guidelines. Thus, similar rates of downramping are experienced by brown trout on a daily-basis during routine load-following flows, so stranding of brown trout during the FLAHG hydrograph is likely to be minor. To reduce these uncertainties, Project O.6 will evaluate how the FLAHG hydrograph affects Brown Trout in Lees Ferry. One unknown impact of the FLAHG hydrograph is how it will affect upstream passage of invasive fish at Pierce Ferry Rapid, hear Lake Mead. Pierce Ferry Rapid is thought to impede upstream movement of nonnative species. Low or high flows associated with the FLAHG hydrograph may change the hydraulics of the rapid at Pierce Ferry, potentially allowing for easier movement of nonnative fish upstream while the FLAHG hydrograph is being tested.

Riparian Vegetation

No major impacts to Riparian Vegetation are anticipated if the FLAHG hydrograph is tested. Dam operations influence riparian plant species differently, depending in part on species-specific drought and flood tolerance. Riparian plant species in the CRe represent a gradient of river flow dependencies (McCoy-Sulentic and others 2017), such that a particular hydrograph may positively impact some species while negatively impacting others. In the context of a FLAHG hydrograph, low flows of 4,000 ft^3/s could desiccate obligate wetland plant species that are strongly dependent on river flows, such as willows, sedges, rushes, potentially reducing their survival (Gorla and others 2015); however, given the short duration of the low flow (5 days) in early springtime, severe impacts are unlikely. We expect this to be more pronounced for species rooted farther away from the river, for shallowly rooted species, and for plants established in quickly draining soils, like sandbars. More drought-tolerant riparian species (*Tamarix* spp., for example) are unlikely to be negatively impacted by the low flows.

The high flow portion of the FLAHG hydrograph will provide water to riparian plants established farther away from the river during the time of year that they start to grow. We expect that for many species this would increase growth, at least for a short period after the flow (Ralston 2010). However, since the high flow portion of the FLAHG hydrograph is similar to high flows during summer peaking operations, plant growth is not anticipated to be measurably higher over the long term. A short duration high flow likely won't negatively impact flood tolerant species, but would be detrimental to flood intolerant (typically drought tolerant) plant species (Stromberg and others 1991, Banach and others 2009).

Spring floods are often used in regulated river systems to naturally support the germination and establishment of cottonwood and willow forests (Rood and others 2003, Rood and others 2005). Spring floods can also benefit nonnative plant species (Ralston 2010). Cottonwood and willows have specific flow requirements for seed germination and juvenile plant growth, which are not met by common dam releases (Stromberg 2001, Stromberg and others 2007), including those of Glen Canyon Dam. Spring floods need to be large enough to clear vegetation to make bare, wet sand and their timing needs to coincide with the period when cottonwoods and willows are seeding. To support recruitment of cottonwood and willow, flood recession must be slow (~2.5 cm per day; species, temperature, and soil substrate dependent), so that the germinating seeds do not dry out (Rood and others 2005). Thus, regular dam operations that follow the FLAHG hydrograph test may erode seedlings (Porter and Kearsley 2001). Herbarium records suggest that a March test of the FLAHG hydrograph is earlier than cottonwood and willow seed release in Grand Canyon, but cottonwood seeds may be released as early as March in some years (L. Stevens, personal observation). Cottonwood (*Populus fremontii*) are in seed in April or May in the Grand Canyon region. Coyote willow (*Salix exigua*) and Goodding's willow (*Salix gooddingii*) are in seed later still, from May to September. Previous studies have indicated that a short-duration March high flow does not contribute to *Tamarix* spp. establishment (Ralston 2010, Mortenson and others 2012), so is likely not a concern for the FLAHG hydrograph.

In summary, obligate riparian species will likely be negatively impacted by the low flow portion of the hydrograph while flood-intolerant species will likely be negatively impacted by the high flow. However, these effects are unlikely to have long-term effects on plant communities. Although the FLAHG hydrograph is unlikely to have long-term effects on CRe riparian vegetation, the FLAHG hydrograph represents a valuable opportunity to study how riparian vegetation is affected by drying and inundation. Project O.4 includes a riparian vegetation study that will use physiological measurements of plants to evaluate these effects.

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