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OPTIMAL TIMING OF HIGH-FLOW EXPERIMENTS FOR SANDBAR DEPOSITION

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Sediment-transport theory and field measurements indicate that the greatest or most efficient deposition of sand in eddies occurs during controlled floods (a.k.a. High-Flow Experiments or HFEs) when the greatest amount of the finest sand is available on the bed of the Colorado River (Topping and others, 2010). Conducting HFEs when the sand on the bed of the Colorado River is depleted and coarse can result in relatively widespread erosion of sandbars during HFEs (Hazel and others, 1999; Schmidt, 1999; Rubin and others, 2002). Here we show that sandbar building during HFEs is maximized during periods following tributary floods that resupply the river with very fine sand. Conversely, sandbars erode during HFEs when the antecedent sand supply is depleted and coarse. HFEs conducted during the fall-winter months of October through January take advantage of having the greatest amount of very fine sand available on the bed of the Colorado River in Marble Canyon. Conducting HFEs in the spring would necessitate lowering the discharges released from Glen Canyon Dam over the winter months in order to retain the very fine sand supplied during the previous summer.

The physical controls on deposition of sand in eddies can be demonstrated through a scaling analysis of the Exner equation, the mass conservation relation between sand in transport and sand in the bed (Grams and others, 2013). This scaling analysis yields the following simple proportionality:

$$\frac{\Delta \eta}{\Delta t} \propto -\frac{\Delta\left(u_*^{4.5} h A_B D_B^{-2.5}\right)}{\Delta x} \tag{1}$$

where Δ indicates a change in the modified variable, η is bed elevation, t is time, u_* is the shear velocity (a measure of flow strength), h is flow depth, A_B is the area of sand covering the bed, D_B is the median grain size of the bed sand, and x is the downstream distance. Because u_* is typically nearly perfectly correlated with velocity, u_* can be taken simply as a proxy for velocity. This proportionality indicates that the greatest change in bed elevation, i.e., the greatest deposition of sand, per unit time is caused by a combination of (listed in decreasing order of importance): (1) the greatest spatial decrease in velocity, (2) the greatest spatial increase in bed-sand grain size, (3) the greatest spatial decrease in flow depth, and (4) the greatest spatial decrease in bed-sand area. Thus, for the case of flow from a main-channel pool into an eddy, the greatest deposition rate in the eddy will occur when A_{B} in the main-channel pool is greatest and/or D_{B} in the main-channel pool is the finest, given that the spatial decrease in velocity and depth into this eddy will be similar during HFEs with similar peak discharge. When the sand in the main-channel pool upstream from the eddy is relatively depleted (thus increasing the spatial increase in A_{B} from the main-channel pool into the eddy) or relatively coarse (thus increasing the spatial decrease in DB from the main-channel pool into the eddy), the effect is to counteract the spatial decrease in u_* that is the dominant driver of sand deposition in the eddy. Therefore, the greatest sandbar building in eddies will occur during the period after tributary floods supply the Colorado River with large amounts of very fine sand.

Empirical results utilizing measurements of sandbar topographic response, bed-sand grain size, and antecedent sand storage during HFEs confirms this theoretical result. We analyze data from only the 1996, 2004, and 2008 HFEs (U.S. Geological Survey, 2019); the topographic surveys conducted immediately before and after HFEs required for our analyses were conducted for those, but not subsequent events. The three segments of the Colorado River in which data were analyzed were: the upper Marble Canyon (UMC) segment, extending from river mile (RM) 0 at Lees Ferry to RM 30; the lower Marble Canyon (LMC) segment, extending from RM 0 to RM 61; and the eastern Grand Canyon (EGC) segment, extending from RM 61 to RM 87. For this analysis, the "high-elevation sandbar volume ratio" is taken as a proxy for $\Delta\eta/\Delta t$ in equation 1, the measured change in sand mass in a river segment between July 1 and the HFE is taken as a proxy for A_{B}, and D_{B} is set equal to the mean β calculated among the suspended-sand measurements collected using suspended-sediment samplers during the peak discharge of the HFE at the gaging station at the downstream end of a river segment. The sandbar volume ratio is defined as the surveyed volume post HFE divided by the surveyed volume pre-HFE above the stage associated with a discharge of 8,000 ft^3/s. The measured change in sand mass in each river segment was calculated with uncertainty using continuous post-2002 sand-transport measurements (Topping and others, 2010). β is a non-dimensional measure of the coarseness of the bed sand in the reach upstream from the gaging station where suspended-sand measurements are made, and is back calculated from these suspended-sand measurements (Rubin and Topping, 2001, 2008). β is well correlated with D_{B} when the D_{B} Rouse number is relatively low, and is well correlated with the amount of very fine bed sand when the D_{B} Rouse number is relatively high (Topping and others, 2018a).

Results from the 2004 and 2008 HFEs show that the high-elevation sandbar volume ratio and the July 1-HFE change in sand mass are strongly positively correlated (Figure 1), as expected based on the implied positive correlation in equation 1 between A_B in the main-channel pool upstream from an eddy and η in the eddy. Among all three river segments analyzed (UMC, LMC, and EGC), the positive correlation between the July 1-HFE change in sand mass and the mean high-elevation sandbar volume ratio during the 2004 and 2008 HFEs is strong (correlation-coefficient r = 0.81; n = 6 cases). Results from the 1996, 2004, and 2008 HFEs show that high-elevation sandbar volume ratios at sandbars nearest the gaging stations where suspended-sediment measurements were made are moderately to strongly negatively correlated with β (Figure 2), as expected based on the implied negative correlation in equation 1 between D_B in the main-channel pool upstream from an eddy and η in the eddy. Among all three river segments analyzed (UMC, LMC, and EGC), the negative correlation between β and the high-elevation sandbar volume ratio in nearby eddies during the 1996, 2004, and 2008 HFEs is also moderate to strong (r = -0.62; n = 10 cases). Importantly, the cases in Figure 1 where the error bars about the mean high-elevation sandbar volume ratio bracket the sandbar volume ratio of unity (the horizontal black line) are cases where at least one of the sandbars that were included in the calculation of the mean ratio eroded during an HFE. Moreover, the cases in Figure 2 with high-elevation sandbar volume ratios less than unity (below the horizontal black line) are cases where sandbars eroded during an HFE. Thus, sandbars will erode during an HFE when the change in sand mass before the HFE, A_B, is relatively small or negative, and sandbars will also erode during an HFE when the bed sand, D_B, is relatively coarse.

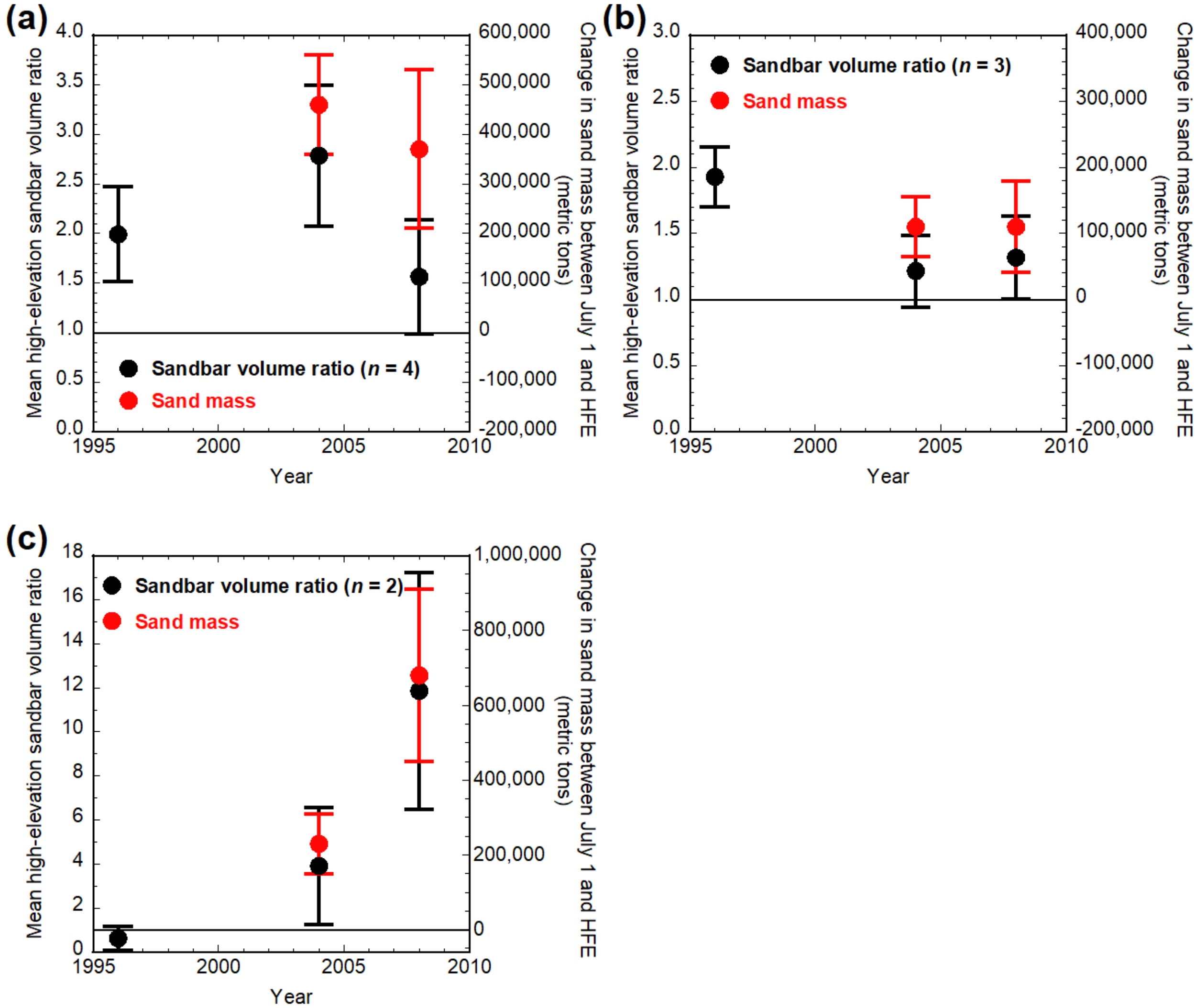

Figure 1. Mean high-elevation sandbar volume ratio and the change in sand mass between July 1 and the start of the HFE plotted for the 1996, 2004, and 2008 HFEs in **(a)** upper Marble Canyon, **(b)** lower Marble Canyon, and **(c)** eastern Grand Canyon. The horizontal black line in each figure panel indicates the mean high-elevation sandbar volume ratio of unity, above which sandbars got larger (i.e., aggraded from sand deposition) at high elevation during that HFE and below which sandbars got smaller (eroded) at high elevation during that HFE. Error bars on the change in sand mass indicate the propagated uncertainty in the sand budget for this river segment, as described in Topping and others (2010). Error bars on the sandbar volume ratio indicate the standard error of the mean. In cases where the mean high-elevation sandbar ratio plots below unity, sandbars generally eroded during that HFE. In cases where the error bar on the mean high-elevation sandbar ratio brackets unity, at least one of the sandbars eroded during that HFE. In only those cases where the error bar on the mean high-elevation sandbar ratio does not bracket unity did sandbars generally get larger during an HFE. The large change in sand mass before the 2008 HFE in the eastern Grand Canyon segment is mostly from large winter floods on the Little Colorado River.

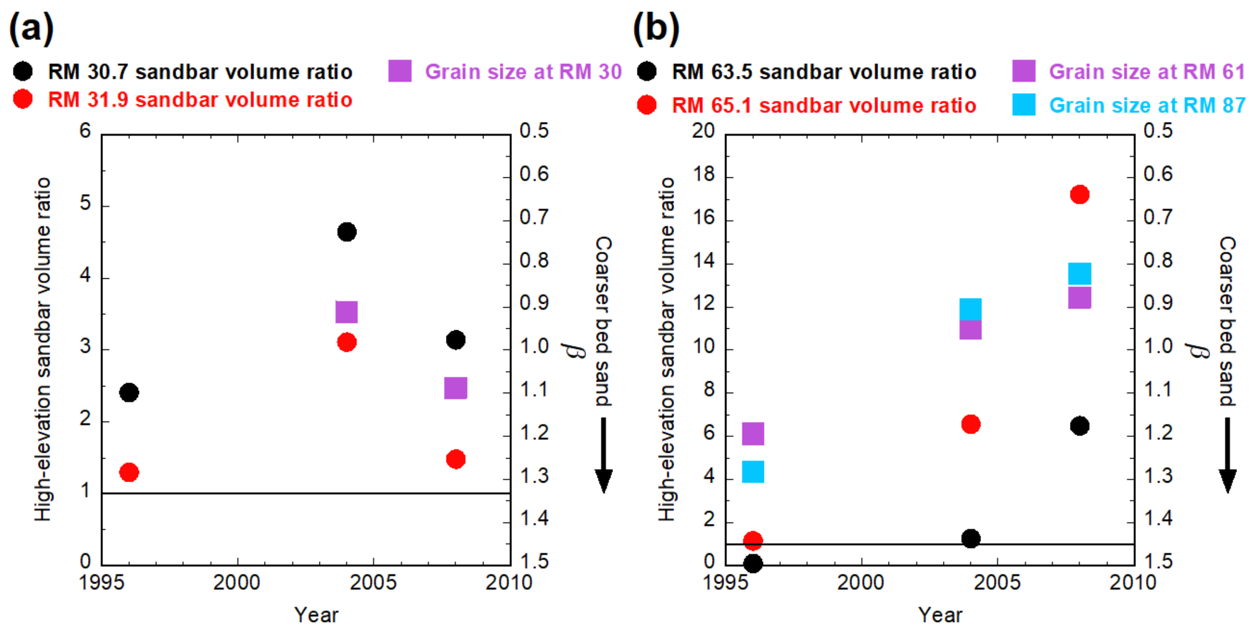

Figure 2. High-elevation sandbar volume ratio and β plotted for the 1996, 2004, and 2008 HFEs for **(a)** the RM 30 gaging station, and **(b)** the RM 61 gaging station. As in Figure 1, the horizontal black line in each figure panel indicates the high-elevation sandbar volume ratio of unity, above which sandbars got larger (i.e., aggraded from sand deposition) at high elevation during that HFE and below which sandbars got smaller (eroded) at high elevation during that HFE. For ease of interpretation, β plotted with its axis reversed such that the coarsest bed-sand grain size is at the bottom of each figure panel. Shown in (a) are the high-elevation sandbar volume ratios from the two sandbars nearest the RM 30 gaging station; shown in (b) are the high-elevation sandbar volume ratios from the two sandbars nearest the RM 61 gaging station. β at the RM 87 gaging station is also plotted in (b) for comparison with β at the RM 61 gaging station. The official U.S. Geological Survey (USGS) name and number of the RM 30 gaging station is the "Colorado River near river mile 30 (09383050)." The official USGS name and number of the RM 61 gaging station is the "Colorado River above Little Colorado River near Desert View, AZ (09383100)." The official USGS name and number of the RM 87 gaging station is the "Colorado River near Grand Canyon, AZ (09402500)." See https://www.gcmrc.gov/discharge_qw_sediment/stations/GCDAMP for a map showing the locations of these gaging stations, and https://www.gcmrc.gov/discharge_qw_sediment/reaches/GCDAMP for a map showing the extents of the upper Marble Canyon, lower Marble Canyon, and eastern Grand Canyon river segments.

Sand is transported relatively quickly as a sand wave following a tributary flood (Topping and others, 2000). In the case of Marble Canyon, the tributary that is the only large supplier of sand is the Paria River; in the case of Grand Canyon, the Little Colorado River also supplies large amounts of sand, but less regularly than does the Paria River. Under 2004-2017 dam releases, HFEs conducted within ~70 to ~140 days of a large Paria River flood fall within the period of maximum bed-sand fining in Marble Canyon following this tributary flood. Lagged-covariance analyses between 2004-2017 Paria River sand loads and bed-sand grain size at downstream gaging stations indicate that the finest persistent bed-sand grain size occurs at RM 30 (in the middle of Marble Canyon) ~70 days after a large Paria River flood, and at RM 61 (at the lower end of Marble Canyon) ~140 days after a large Paria River flood (Topping and others, 2018b). Thus, given that the months of largest sand input from the Paria River are August and September, HFEs conducted during the months of October through January have the greatest amount of very fine sand available on the bed of the Colorado River in Marble Canyon to rebuild eddy sandbars. The rates of sand transport and coarsening in the Colorado River during the periods between tributary floods are controlled by dam operations. Therefore, lower discharges would be required over the winter months to increase the retention period of this very fine sand for spring HFEs conducted > 200 days after large summer sand inputs from the Paria River.

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EVALUATION OF SAND TRANSPORT PREDICTIONS FOR THE COLORADO RIVER BELOW GLEN CANYON DAM DURING RECENT HIGH-FLOW EXPERIMENTS

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In 2010, Wright and others (2010) published a numerical model designed for the simulation of sand transport along the Colorado River downstream from Glen Canyon Dam (model domain is from Lees Ferry to Phantom Ranch). Since then, the sand routing model (SRM) has been used, along with real-time data on sand transport, to plan for controlled flood releases from Glen Canyon Dam (High-Flow Experiments or HFEs). HFEs are conducted based on sand accumulation triggers in Marble Canyon and the hydrograph is designed to export a comparable volume of sand as that accumulated pre-HFE. The SRM is used by Reclamation in the design of the HFE hydrograph. Thus, the accuracy of the SRM is a critical component of the HFE strategy.

The SRM as published in 2010 was calibrated and validated based on data from September 2002 through March 2009. This period included HFEs in November 2004 and March 2008. Although informal updates to the model have been conducted periodically since publication, no formal evaluation of model performance had been performed post-publication. Since March 2009, five HFEs have been conducted: 2012, 2013, 2014, 2016, and 2018, all in November. Though the SRM is physically based, it also contains empirical calibration parameters and the recent HFEs provide an excellent test of the original model calibration.

The model was calibrated to the more recent time period using a similar procedure as the original calibration: varying the coefficient in the relationship between sand concentration and discharge in order to best match the measured sand mass balance over the time period. This re-calibration resulted in small changes in model results for upper Marble Canyon, and moderate changes in results for lower Marble Canyon. Both the original model and the updated model results fall within the uncertainty of the measured mass balance values.

Once re-calibrated, model results for the seven HFEs and the accumulation periods preceding the HFEs were evaluated versus measured data. During accumulation periods, the model reproduced the distribution between upper and lower Marble Canyon well, and errors (residuals from measurements) were typically less than 10% (6% mean) and unbiased. During HFEs, model errors were typically less than 20% (17% mean) and slightly negatively biased, due to underprediction of HFE export in 2004 and 2008. For the five more recent HFEs, model errors were lower, averaging 10%, and unbiased.

Finally, an important component of the HFE protocol is to design hydrographs that do not drive the mass balance negative during an HFE (that is, export more sand than had accumulated prior to the HFE). To address this, the updated model was evaluated for how well it predicts the volume of sand remaining in Marble Canyon following the HFEs. The model was able to reproduce the range of outcomes in the measured data quite well. For the HFEs in 2012, 2014, and 2018, the model correctly predicted that about 50% of the accumulated sand remained following the HFEs. In contrast, in 2013 almost 80% of the sand remained following the HFE and in 2016 less than 10% remained; the model reproduced these values as well, to within 5%.

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SANDBAR DEPOSITION CAUSED BY HIGH-FLOW EXPERIMENTS ON THE COLORADO RIVER DOWNSTREAM FROM GLEN CANYON DAM: NOVEMBER 2012 – NOVEMBER 2018

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INTRODUCTION

The streamflow regime and sand supply of the Colorado River have been affected by the presence and operations of Glen Canyon Dam since filling of Lake Powell began in March 1963. Consequent changes in river morphology have included decreases in the size and abundance of sandbars used as campsites in Grand Canyon National Park (Dolan and others, 1974; Schmidt and Graf, 1990; Kearsley and others, 1994). The sandbars that occur along the banks of the Colorado River and create camping beaches and backwaters and are habitat used by native fish (Dodrill and others, 2015) are inherently unstable features of an active river channel (Schmidt, 1990). The deposits form when sand, carried in suspension in the main channel of the Colorado River, settles in the lower velocity recirculating currents of eddies (Rubin and others, 1990; Schmidt, 1990). When the flows that resulted in bar deposition recede, leaving a fresh sand deposit, the deposits begin eroding. Decreases in the magnitude and frequency of annual floods have resulted in decreased opportunities for deposition. The complete elimination of sand sources upstream from Glen Canyon Dam decrease the supply that is available when high flows do occur. Finally, the increase in the magnitude of flows throughout the year coupled with daily fluctuations for hydropower generation accelerate rates of erosion for remaining sandbars (Hazel and others, 2010).

Controlled floods, consisting of short-duration releases above the capacity of the hydroelectric powerplant, were first proposed as a method for rebuilding sandbars in the early 1990s (U.S. Department of the Interior, 1995). Findings from experimental controlled floods in 1996, 2004, and 2008 indicated that high-flow releases could be used to rebuild sandbars, but also revealed that sand supply was limited and that releases should be timed to follow tributary sand inputs (Schmidt and Grams, 2011; Wright and Kennedy, 2011). In 2012, the US Department of the Interior adopted a strategy to release controlled floods, termed High-Flow Experiments (HFEs), based on the timing and quantity of sand inputs from the Paria River (Grams and others, 2015; US Department of the Interior, 2012; 2016). The purpose of this study is to describe the response of sandbars to HFEs conducted between 2012 and 2018.

METHODS

Changes in sandbar size and volume were determined by inspection of images acquired by digital remote cameras and by analysis of topographic surveys. Daily images at up to 45 long-term monitoring sites are recorded by digital cameras that are typically mounted at vantage points across the river from the monitoring sites. Images from the cameras are collected on periodic river trips and analyzed to determine changes in sandbar size. Sandbar size is assessed categorically for each site immediately after each HFE, six months after each HFE, and 11 months after each HFE. The camera equipment, deployment locations, and methods of analysis are described in detail in Grams and others (2018) and photographs are available for viewing at www.gcmrc.gov/sandbar. Detailed topographic surveys are conducted at each long-term monitoring site between late September and mid-October annually. The methods for data collection, processing and analysis are described by Hazel and others (2010) and data are available at www.gcmrc.gov/sandbar. Here, normalized sandbar volume for each of the sandbar types described by Mueller and others (2018) is reported. Normalized sandbar volume is defined as the volume of sand measured for a particular survey divided by the estimated maximum potential volume of sand-storage for that site. The volume for each survey is computed as the difference between the topographic surface measured for each survey and a computed minimum sandbar surface. The minimum sandbar surface is a composite surface defined as the lowest elevation ever measured at each 1-m grid cell among all surveys for each site (Hazel and others, 2010). The maximum surface is correspondingly defined as the highest elevation ever measured at each 1-m grid cell among all surveys. The maximum potential volume of sand storage for each site is the difference between the composite maximum surface for each site and the composite minimum surface for each site. Thus, these minimum and maximum elevation surfaces are relative only to the time frame of sandbar measurements (1990 to 2018 for most sites).

The effects of the 2012 HFE, which had lower downramp rate than other HFEs, on sandbar topography was evaluated by analysis of the slope of the sandbar surfaces. For each of the three sites surveyed following the 2012 HFE, we computed sandbar slope as the gradient over a 0.75 m by 0.75 m moving window over a grid with 0.25-m cell size using the “slope” tool in ArcGIS version 10.5.1. We categorized the results into areas with slope greater than 8 degrees and areas with slope less than 8 degrees. The threshold of 8 degrees was used, because that is the approximate threshold for areas considered flat enough to use for camping (Kearsley and others, 1994; Hadley and others, 2018).

RESULTS

HFEs have been released in five of the seven years since the HFE protocol was adopted. The average sand inputs from the Paria River during the July 1 to November 1 period among the years HFEs occurred was 1,076,000 metric tons (Mg) (Table 1). The average among all years in this period was 974,000 Mg, which is only slightly greater than the 900,000 Mg long-term average July-November Paria River sand supply that was estimated when the strategy for the HFE protocol was developed (Wright and Kennedy, 2011). HFEs were triggered with as little as 688,000 Mg of sand in 2012 and as much as 1.8 million Mg of sand in 2013 (Table 1). Sand inputs in 2015 were enough to trigger an HFE, but the HFE was cancelled owing to the detection of a reproducing population of invasive green sunfish (*Lepomis cyanellus*) in the 20-km reach immediately downstream from Glen Canyon Dam. The HFEs varied in magnitude from 36,500 ft^3/s to 44,500 ft^3/s and varied in duration between 65 and 104 hours (duration computed as period of discharge greater than 31,500 ft^3/s). The 2013, 2014, and 2016 HFEs had similar hydrograph shape – steady peak flow and downramp rate of ~1,300 ft^3/s per hour. The 2018 HFE had a steady peak flow and downramp rate of ~1,700 ft^3/s per hour. The 2012 HFE had a peak flow duration of just 24 hours followed by a relatively gradual downramp rate of approximately 250 ft^3/s per hour for 60 hours until discharge was 31,500 ft^3/s. This was followed by a rapid downramp to normal operations.

Each of the HFEs since 2012 has resulted in observable deposition (minor or major gains in sandbar size) at more than 50 percent of the monitoring sites (Table 2). In 2012 and 2013, visible gains in sandbar size were observed at 52 percent of the monitoring sites. Since 2014, gains were observed at 56 percent or more of the sites. The largest increase was observed in 2018, when minor or major gains in sandbar size were observed at 66 percent of the monitoring sites. The HFE that occurred in November 2018 was the first HFE since the one conducted in March 2008 that was released following large sand inputs from the Little Colorado River, in addition to sand inputs from the Paria River. Erosion of the HFE-deposited sand occurred at most sites and the observable size was similar to the pre-HFE sandbar size within six to eleven months following each HFE. Most sandbars among the monitoring sites respond consistently. Among the 43 sites, 58 percent usually increase in size and 21 percent are usually unchanged (Table 3). The response was variable at 12 percent of the sites and 9 percent of the sites typically decreased in size.

The observed sandbar size based on inspection of the images was generally consistent with the results based on annual topographic surveys that were conducted approximately eleven months following each HFE. These data indicate there were stable or slight upward trends in sandbar volume at the monitoring sites between 2012 and 2018 (Figure 1). These trends were strongly significant for wide reattachment bars. Reattachment bars are typically large sandbars that form in the central part of the eddy (Schmidt, 1990). The trends were weakly significant for narrow and medium reattachment bars and separation bars. Separation bars tend to be smaller than reattachment bars and form adjacent to debris fans at the upstream end of eddies. Trends were not significant for undifferentiated and upper pool bars (Table 4). Undifferentiated bars form along the banks in the central part of the eddy and upper pool bars form in eddies upstream from debris fans. Increases in sandbar volume between 2003 and 2018 were significant for all bar types except undifferentiated bars and separation bars (Table 4).

The 2012 HFE with more gradual downramp rate (Table 1) resulted in flatter sandbars than were observed following the 2008 HFE at two of the three sites were topographic surveys were completed after both high flows. At river mile (RM) 9 there was a 9 percent increase in the proportion of the sandbar with slope less than 8 degrees and at RM 30 there was a 17 percent increase in the proportion with slope less than 8 degrees (Table 5). At RM 47 the proportion of the sandbar with slope less than 8 degrees decreased by 9 percent.

CONCLUSIONS

Each of the five HFEs that has been released from Glen Canyon Dam between November 2012 and November 2018 has resulted in deposition at more than 50 percent of 44 long-term sandbar monitoring sites in Marble Canyon and Grand Canyon. That deposition has also resulted in small cumulative increases in sandbar volume at those same monitoring sites. Cumulative increases in sand volume between 2003 and 2018 are significant at reattachment bars and at upper pool bars. Hydrograph shape appears to affect sandbar topography for at least some sites. The lower downramp rate used in 2012 resulted in sandbar topography that was less steep compared to the downramp rate used in the 2008 HFE. However, because the adjusted hydrograph with lower downramp rate was tested in only one year and because topographic surveys were only available for three sites, it is uncertain whether this response would be consistent among many sites or repeatable in future HFEs.

In four out of the five years with HFEs, the sand mass balance for the July 1 to December 1 accounting period has been significantly positive and in one year the sand mass balance was indeterminant (Table 1). Thus, the objective of the HFE Protocol to cause deposition on sandbars and increases in sandbar size without causing decreases in sand storage in Marble Canyon (US Department of the Interior, 2016) was achieved or exceeded each year.

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Table 1. Sand supply, sand mass balance, and hydrograph parameters for each High-Flow Experiment (HFE) between 2012 and 2018.

Year	Paria sand supply: Jul 1 - Nov 1 (Mg)*	Marble Canyon sand mass balance: Jul 1 - Dec 1 (Mg)**	HFE start date	HFE Magnitude	HFE duration (hours)***	HFE downramp rate (ft^3/second/ hour)
2012	688,000	**310,000**	19-Nov	44,500	84	1,800
2013	1,856,000	**1,450,000**	11-Nov	37,000	100	1,333
2014	1,213,000	**690,000**	10-Nov	38,000	104	1,318
2015	1,168,000	**1,010,000**	no HFE			
2016	843,800	41,600	7-Nov	36,500	99	1,262
2017	269,100	**81,000**	no HFE			
2018	777,000	**234,000**	5-Nov	39,500	65	1,735

* Paria River sand supply in metric tons (Mg) computed on https://www.gcmrc.gov/discharge_qw_sediment/.

** Sand mass balance computed on https://www.gcmrc.gov/discharge_qw_sediment/. Each value is the estimated zero bias mass balance. Where uncertainty (not shown) is less than the zero bias estimate, values are shown in bold. For values not shown in bold, uncertainty is greater than the estimate and the mass balance is indeterminate.

*** Duration computed as period of discharge greater than 31,500 ft^3/s.

Table 2. Observed change at indicated percentage of sites monitored by remote camera following each High-Flow Experiment (HFE).

Observed response	2012 HFE (n = 33)	2013 HFE (n = 42)	2014 HFE (n = 42)	2016 HFE (n = 43)	2018 HFE (n = 43)	Average
			Immediately following HFE			
Large deposition	12%	19%	14%	14%	12%	14%
Moderate deposition	39%	33%	43%	42%	54%	42%
Negligible change	39%	36%	31%	33%	22%	32%
Moderate erosion	9%	10%	10%	7%	10%	9%
Large erosion	0%	2%	2%	5%	2%	2%
			Six months following HFE			
Large deposition	0%	0%	0%	0%		0%
Moderate deposition	30%	26%	18%	14%		22%
Negligible change	48%	52%	45%	76%		55%
Moderate erosion	21%	17%	33%	7%		19%
Large erosion	0%	5%	5%	2%		3%
			Eleven months following HFE			
Large deposition	0%	0%	0%	0%		0%
Moderate deposition	18%	7%	0%	9%		9%
Negligible change	70%	55%	59%	74%		64%
Moderate erosion	12%	36%	37%	14%		25%
Large erosion	0%	2%	5%	2%		2%

Table 3. Change in sandbar size at monitoring sites based on interpretation of images collected by remote cameras. Sandbar change is categorized as: large deposition (value of +2), moderate deposition (+1), negligible change (0), moderate erosion (−1), or large erosion (−2).

Site	2012	2013	2014	2016	2018	Typical response*
0025L	1	2	1	1	1	Deposition
0081L	1	1	1	1	1	Deposition
0089L	1	2	0	1	1	Deposition
0166L	0	0	1	0	1	Negligible change
0220R	2	1	0	0	1	Deposition
0235L		1	2	1	1	Deposition
0307R	1	0	1	2	0	Deposition
0319R		2	1	2	2	Deposition
0333L		0	-1	0	1	Variable
0414R	0	-1	-1	-2	0	Erosion
0434L	0	0	0	0	0	Negligible change
0445L	0	0	0	0	1	Negligible change
0450L	2	0	1	2	2	Deposition
0476R	0	1	2	1	0	Deposition
0501R	0	1	0	0	1	Negligible change
0515L	-1	2	-1	-1	1	Erosion
0559R	0	0	1	1	-2	Variable
0566R		1	2	1	1	Deposition
0629R		0	1	0	0	Negligible change
0651R	2	2	1	2	2	Deposition
0658L	0	-1	-2	-2	-1	Erosion
0661L	1	1	2	1	2	Deposition
0688R	1	2	1	1	2	Deposition
0701R				2		Deposition*
0817L	1	1	1	1	1	Deposition
0845R		0	1	1	1	Deposition
0876L	0	0	0	0	0	Negligible change
0917R	-1	-2	0	0	0	Negligible change
0938L	1	0	0	1	1	Deposition
1044R	1	0	1	0	1	Deposition
1194R	2	2	2	2		Deposition
1227R	0	1	2	0	1	Deposition
1232L		-1	0	1	-1	Variable
1377L	0	-1	-1	-1	0	Erosion
1459L	1	1	1	1	1	Deposition
1671L		1	1	1	1	Deposition
1726L	-1	1	0	0	-1	Variable
1833R	1	1	1	1	1	Deposition
1946L	0	1	0	-1	-1	Variable
2023R	1	2	1	0	1	Deposition
2132L		0	1	1	1	Deposition
2201L		0	0	0	1	Negligible change
2255R	0	0	0	1	0	Negligible change

*Typical response was assigned if there were at least three occurrences of the same response. If there were not three occurrences of the same response, the typical response was assigned as "variable."
**At site 0701R, deposition was assigned as the typical response based on direct observation, although images were not available for some HFEs because of camera failure.

Table 4. Trends in normalized sandbar volume based on annual topographic surveys. Slope was determined by simple linear regression and significance evaluated by F-test.

Sandbar Type	Slope of trend in normalized volume (2012-2018)	Significance of trend (p-value)	Slope of trend in normalized volume (2003-2018)	Significance of trend (p-value)
Narrow reattachment bars	3.16E-05	0.32	2.62E-05	0.01
Medium reattachment bars	1.60E-05	0.25	2.34E-05	0.001
Wide reattachment bars	2.43E-05	0.08	2.11E-05	< 0.001
Undifferentiated eddy bars	1.68E-05	0.5	1.49E-05	0.25
Upper pool eddy bars	1.99E-05	0.52	4.27E-05	< 0.001
Separation bars	-3.82E-05	0.18	2.44E-06	0.74

Table 5. Sandbar slope following the 2008 and 2012 High-Flow Experiments for three sites in Marble Canyon.

	RM 9		RM 30		RM 47	
	2008	2012	2008	2012	2008	2012
Area analyzed (m^2)	18,292	18,292	17,757	17,869	29,434	29,888
Slope less than 8 degrees	42%	51%	37%	54%	63%	54%
Slope greater than 8 degrees	58%	49%	63%	46%	37%	46%

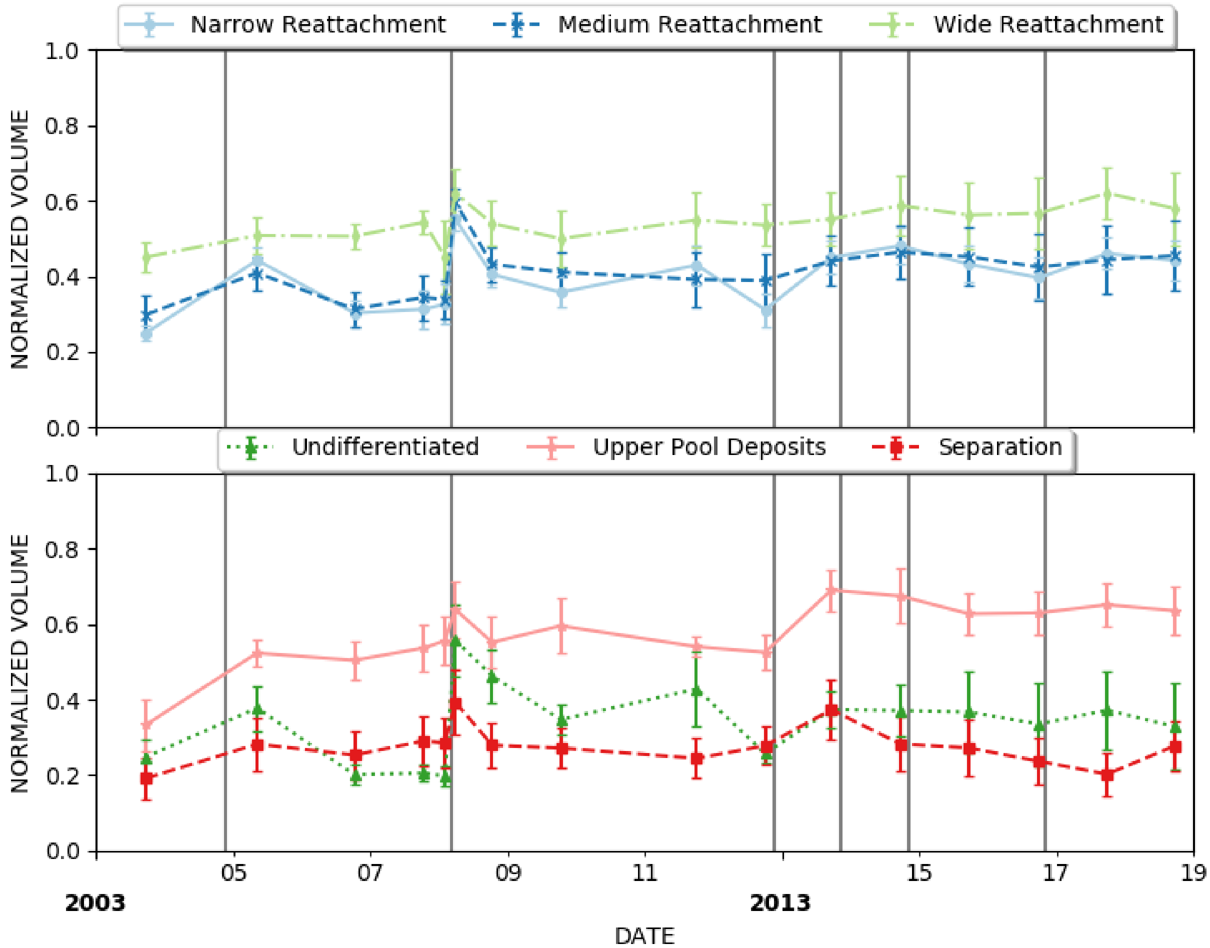

Figure 1. Normalized sandbar volume for long-term sandbar monitoring sites. Error bars are the standard error of the mean among the number of sites in each category. There are 9 narrow reattachment bar sites, 11 medium reattachment bar sites, 5 wide reattachment bar sites, 6 undifferentiated sites, 6 upper pool sites, and 6 separation bar sites (Mueller and others, 2018).

EFFECTS OF HIGH-FLOW EXPERIMENTS ON RIPARIAN VEGETATION RESOURCES IN GRAND CANYON

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INTRODUCTION

Flood events have historically had a strong impact on riparian vegetation within Grand Canyon. Pre-dam sandbars were nearly devoid of perennial riparian vegetation due to the magnitude and frequency of periodic floods (Turner and Karpiscak, 1980). Vegetation has increased since dam closure (Waring, 1995), particularly since the early 1990s (Sankey and others, 2015). This increase in vegetation is attributable to multiple aspects of dam operations, including the low magnitude and duration of High-Flow Experiments (HFEs), specifically flows at 45,000 cfs or smaller over 96 hours. Thus, we begin by providing a broader context for understanding vegetation change, and how other factors interact with HFEs to determine their influence on riparian vegetation. We then discuss the potential mechanisms by which HFEs may impact vegetation, the empirical evidence for those impacts and associated confidence in that evidence, and future research approaches to better fill these gaps in our understanding.

Hydrological Zones – Riparian vegetation within Grand Canyon is distributed across three distinct hydrological zones: 1) the active channel (AC) – area susceptible to daily inundation from hydropeaking (flows up to 25,000 cfs); 2) the active floodplain (AF) – area susceptible to HFEs (flows up to 45,000 cfs); and 3) the inactive floodplain (IF) – area flooded approximately annually pre-dam, but now only very rarely (flows over 45,000 cfs) (Palmquist and others, 2018). The potential effects of HFEs differ between these hydrological zones due to differences in exposure of aboveground tissues to disturbance and inundation, and rooting depth relative to river stage (Butterfield and others, 2018).

Hydropeaking – Hydropeaking, rapid fluctuations in water levels due to power generation, can select for particular plant functional strategies, which in turn influence the sensitivity of vegetation to HFEs (Bejarano and others, 2018a). In general, hydropeaking selects for species that are easily dispersed (local examples include tamarisk (*Tamarix* sp.), arrowweed (*Pluchea sericea*), coyote willow (*Salix exigua*), seep-willow (*Baccharis* spp.), and common reed (*Phragmites australis*)); flexible (e.g., coyote willow, seep-willow), flood tolerant (e.g., coyote willow, common reed) and clonal (e.g., arrowweed, common reed, coyote willow). When hydropeaking is combined with HFEs of low magnitude and duration, this has been found to select for a narrow set of species with specific functional strategies in other dryland river systems (Bejarano and others, 2018b). Thus, hydropeaking may be a strong selective force in structuring the plant community such that it is particularly unresponsive to current HFEs. Whether hydropeaking has been such a strong selective force in Grand Canyon is an open area of research (please see section 5.1 below).

Increased Base Flows – The rate of vegetation expansion in the AF shows a sharp increase in the early 1990s, coinciding with a step-change increase in baseflow levels (Sankey and others, 2015; U.S. Department of the Interior, 1996). While not conclusive evidence, this pattern suggests that a shallower groundwater table has increased soil moisture availability to riparian vegetation, particularly species with only moderately deep root systems such as arrowweed (~1.3m; Stromberg, 2013). This increase in vegetation in response to greater groundwater availability may reduce the physical impact of HFEs on vegetation (e.g., uprooting stems) by slowing flow velocities.

Timing of HFEs – Pre-dam floods typically occurred during the late spring and early summer (Topping and others, 2000), when both native and non-native riparian species respond via regeneration from seed (Mortenson and others, 2012). This is also a period of time when vegetation is rapidly growing, and high temperatures and low humidity result in high water demand. In contrast, since the implementation of the HFE protocol in 2012, HFEs have occurred during the late fall, when the majority of riparian plant species are dormant. The asynchronous fall timing of HFEs with vegetation growth and reproduction greatly reduces the potential for either positive or negative impacts of HFEs on vegetation cover, plant performance, or reproduction.

POTENTIAL MECHANISMS OF HFE IMPACTS AND EMPIRICAL SUPPORT

Disturbance – Impacts of physical disturbance can be distinguished by vegetation removal, vegetation burial, and seed stratification and scarification. We are quite confident that HFEs do not result in significant vegetation removal (Kearsley and Ayers, 1999; Kennedy and Ralston, 2011; Ralston, 2010), which provided the justification for non-flow vegetation management that includes mechanical vegetation removal (i.e., by National Park Service vegetation management staff) outlined in the Long-Term Experimental and Management Plan (U.S. Department of the Interior, 2016). We are also quite confident that vegetation burial is having a neutral to positive impact on the dominant woody vegetation (e.g., arrowweed, willow) given the propensity toward clonal growth. Many clonal species, such as arrowweed, benefit from sand burial (Catford and Jansson, 2014). We have no direct evidence for effects of HFEs on seed stratification (creation of conditions that support seed germination), but we do know that species such as mesquite (*Prosopis glandulosa*) and catclaw acacia (*Acacia greggii*) benefit from scarification of their thick seed coats by sand (Baskin and Baskin, 1998), as well as burial. Thus, we are moderately confident that these species benefit from HFEs with respect to regeneration from seed.

Inundation – Inundation by water has variable effects on plants depending upon their physiological adaptations (Silvertown and others, 2015). We are quite confident that inundation by HFEs keeps xeric species (e.g., brittlebush, creosote, acacia) from expanding significantly into the AF (Butterfield and others, 2018), and that it is not significantly impacting species that are dominant in the AF due to the short duration of HFEs (Sankey and others, 2015). In other words, species in this system that are adapted to any degree of flooding are not impacted by 3-4 days of inundation characteristic of HFEs since the implementation of the protocol. While potential future increased HFE duration will almost certainly not impact some AF species such as tamarisk, mature plants of which have been shown to endure flooding for weeks or months (Zouhar, 2003), we are not certain of the flooding sensitivity of other species such as arrowweed (see section 5.2 below).

Soil Moisture – We are moderately confident that HFEs are not supplementing soil moisture to woody plant species. Based on niche models that we have developed (Butterfield and others, 2018), and data on rooting depths of the dominant woody riparian species in this system (Stromberg, 2013), we are quite certain that persistent, dominant woody species can consistently access ground water from the river. Thus, the addition of a soil moisture pulse from HFEs is not likely to further benefit woody plants, though species with dimorphic root systems (shallow and deep) may benefit slightly, assuming they are active in the fall. We are moderately confident that HFEs are enhancing conditions for herbaceous species, based on their tendency to occur in habitats with lower inundation frequencies than optimal for these species (Butterfield and others, 2018).

Seasonality – We are quite confident that fall HFEs have little to no impact on vegetation (Ralston and others, 2014), due to the lack of physiological or reproductive activity during the fall. The one caveat is that herbaceous species in general may be benefitting slightly from the brief soil moisture pulse provided by HFEs. Seedlings of some species that germinate during monsoon season, such as mesquite (*Prosopis glandulosa*) and catclaw acacia (*Acacia greggii*), may be washed out by HFEs, but we do not have direct evidence to support this. On the other hand, HFEs in the late spring or early summer could be moderately impactful by enhancing soil moisture during a typically hot and dry time of year (moderate confidence), and by creating conditions for spring-germinating species such as cottonwood (*Populus fremontii*) or tumbleweed (*Salsola tragus*, low confidence), though other factors also strongly influence regeneration dynamics (Ralston and others, 2014).

SUMMARY

HFEs create specific habitat conditions with respect to inundation and depth to groundwater that support specific plant species and primarily impact vegetation through maintenance of the AF. Disturbance, inundation duration, soil moisture enhancement and the current timing of HFEs have relatively minimal overall impact on current vegetation. This is in large part due to the comparatively more important effects of daily and yearly dam operations such as hydropeaking and base flows for riparian vegetation. The minimal effect of current HFEs on vegetation is also due to the relatively low magnitude and duration of current HFEs in comparison to pre-regulation floods under which many aspects of the riparian vegetation community originally developed. Implementation of spring HFEs is unlikely to substantially impact vegetation unless the flood magnitude and/or duration are greatly increased.

UNKNOWNS TO ADDRESS

Hydropeaking as a Selective Force – The degree to which hydropeaking has influenced the sensitivity of vegetation to HFEs is an open question. Specifically, it is important to understand whether certain species from the regional species pool (those with the ability to disperse to riparian habitat in Grand Canyon) have been excluded due to hydropeaking. *Ex situ* experiments could be conducted to determine the sensitivity of different species to hydropeaking and the mechanisms by which it may or may not have influenced current species composition in Grand Canyon. The impacts of inundation during night versus day is also a potentially important unknown that can be studied with *ex situ* experiments.

Flooding Sensitivity of Important Species – Arrowweed has become an abundant riparian plant species in the AF on sandbars used for camping throughout the canyon, but particularly in the western end (Durning and others, 2018). Arrowweed is perceived to have a negative impact on recreation resources. Arrowweed is common on other regulated segments of the Colorado River (Vandersande and others, 2001), suggesting that flow regulation may be creating optimal conditions for this species in Grand Canyon (see Introduction – Hydropeaking above). While other dominant AF species such as tamarisk and mesquite are highly tolerant of long inundation durations, there is little information regarding flooding sensitivity of arrowweed (but see Vandersande and others, 2001), though it is likely to benefit from burial by sand (Catford and Jansson, 2014). *Ex situ* experiments testing the flooding tolerance of arrowweed and other important species for extended periods could help to identify alternative flow-related vegetation management strategies for future implementation.

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HIGH ELEVATION SAND/CULTURAL SITES: THE RESPONSE OF SOURCE BORDERING AEOLIAN DUNEFIELDS TO THE 2012-2016 HIGH-FLOW EXPERIMENTS OF THE COLORADO RIVER IN GRAND CANYON

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Glen Canyon Dam has reduced downstream sediment supply to the Colorado River by about 95% in the reach upstream of the Little Colorado River confluence and by about 85% below the confluence (Topping and others, 2000). Operation of the dam for hydropower generation has additionally altered the flow regime of the river in Grand Canyon, largely eliminating pre-dam low flows (i.e., below 8,000 ft^3/s) that historically exposed large areas of bare sand (U.S. Department of the Interior, 2016a; Kasprak and others, 2018). At the same time, the combination of elevated low flows coupled with the elimination of large, regularly-occurring spring floods in excess of 70,000 ft^3/s has led to widespread riparian vegetation encroachment along the river, further reducing the extent of bare sand (U.S. Department of the Interior, 2016a, Sankey and others, 2015). Kasprak and others (2018) report that the areal coverage of bare sand has decreased by 45% since 1963 due to vegetation expansion and inundation by river flows. Kasprak and others (2018) forecast that the areal coverage of bare sand in the river corridor will decrease by an additional 12% by 2036, due to further vegetation encroachment and erosion.

The changes in the flow regime, the reductions in river sediment supply and bare sand, and the proliferation of riparian vegetation has reduced the transfer (termed “connectivity”) of sediment from the active river channel (e.g. sandbars) to dunefields, terraces, and other river sediment deposits in the adjoining landscape (U.S. Department of the Interior, 2016a; Draut, 2012; East and others, 2016; Kasprak and others, 2018; Sankey and others, 2018a,b). These processes have resulted in the erosion of upland landscapes and have affected the condition and physical integrity of archaeological sites in Marble and Grand Canyons. Many archaeological sites and other evidence of past human activity are now subject to accelerated degradation due to reductions in sediment connectivity under current dam operations and riparian vegetation expansion tied to regulated flow regimes (U.S. Department of the Interior, 2016a; East and others, 2016).

The Glen Canyon Dam Long-term Experimental and Management Plan Final Environmental Impact Statement (LTEMP EIS; U.S. Department of the Interior, 2016a) predicts that conditions for achieving the goal of preservation of cultural resources, termed “preservation in place,” will be enhanced as a result of implementing the selected alternative. High-Flow Experiments (HFEs) are one component of the selected alternative that will be used to resupply sediment to sandbars in Marble and Grand Canyons, which in conjunction with targeted vegetation removal, is expected to resupply more sediment via wind transport from HFE-deposited sandbars to archaeological sites, depending on site-specific riparian vegetation and geomorphic conditions. Although HFEs have been shown to directly erode terraces that contain archaeological sites in Glen Canyon National Recreation Area (East and others, 2016; U.S. Department of the Interior, 2016a), HFEs have been shown to rebuild or maintain sandbars that provide sand to resupply aeolian dunefields containing archaeological sites throughout Marble and Grand Canyons (East and other, 2016; Sankey and others, 2018b).

Kasprak and others (2018) recently inventoried the spatial distribution of bare, unvegetated Colorado River sand by area in Marble and Grand Canyons. They determined that currently:

- Approximately 1/3 of the total area of river sand is located within the river channel below the stage of baseflows (8,000 ft^3/s), and thus nearly always inundated by the river.
- Approximately 1/6 is located above the baseflow stage but below the maximum stage achieved by HFEs (45,000 ft^3/s); this, for example, would be sand within the subaerial portions of river sandbars.
- Approximately 1/2 of the total area of river sand is found at relatively high elevations above the maximum stage achieved by HFEs.

Most of the comparatively large total area of river sand found at high elevations is associated with aeolian dunefields, many of which contain archaeological sites. Sankey and others (2018a,b) recently determined that there are 57 source-bordering aeolian dunefields (SBDs) along the Colorado River in Grand Canyon that are relatively large (spatially contiguous areas of unvegetated sand > 1000 m^2) and have dune morphology that is visible in high-resolution aerial overflight imagery acquired by the Grand Canyon Monitoring and Research Center (GCMRC). There are at least another 60 similarly large areas of unvegetated sand (aeolian-dominated areas, ADAs) at which aeolian processes are a primary mechanism of geomorphic change; although dune morphology is not visible in aerial imagery, other indicators of recent aeolian sand transport (e.g., coppice dunes and shadow dunes in the lee of shrubs, boulders, or arroyo channels) have either been identified in the field (East and others, 2016) or are visible in aerial imagery. While HFEs do not directly inundate most of these SBDs and ADAs, they do resupply them with river sand by rebuilding upwind sandbars.

Sankey and others (2018b) used a legacy of high-resolution lidar remote-sensing and meteorological data, to characterize the response of four SBDs during four HFEs in 2012, 2013, 2014, and 2016. They found that aeolian sediment resupply unambiguously occurred in half of the instances (8 of the 16) of HFE flooding adjacent to the dunefields. Resupply attributed to individual floods varied substantially among sites, and occurred with four, three, one, and zero floods at the four sites, respectively. Sankey and others (2018b) infer that the relative success of HFEs as a regulated-river management tool for resupplying sediment to dunefields is analogous to the frequency of resupply observed for river sandbars, in that sediment resupply at sandbars monitored by GCMRC was estimated to have occurred for roughly half of the instances of recent HFEs (Grams and others, 2015). Importantly, Sankey and others (2018b) found that dunefield sediment storage increased cumulatively when HFEs were conducted consistently on an annual basis, whereas sediment storage decreased at 3 of the 4 dunefields during the 1-year hiatus from HFE in 2015. Analysis in Project D during FY2018 has since determined that sediment storage increased at the individual archaeological sites within the dunefields analyzed by Sankey and others (2018b) owing to resupply from 2012-2016 HFE sand.

Ongoing work is continuing to quantify the geomorphic effects of regular and experimental dam operations as well as evaluating the geomorphic effects of riparian vegetation expansion and management, focusing on effects of HFEs on the supply of sediment to cultural sites and dunefields through 2036, as specified under the LTEMP (see U.S. Department of the Interior, 2016ab, and also see “Project D” of the Glen Canyon Dam Adaptive Management Program Triennial Budget and Work Plan—Fiscal Years 2018–2020). The data and analyses from that ongoing work will allow the Glen Canyon Dam Adaptive Management Program (GCDAMP) to objectively evaluate whether and how these non-flow and flow actions affect cultural resources, vegetation, and sediment dynamics. The past, present, and likely future expansion of riparian vegetation onto sandbars reduces the supply of HFE sand for dunefields and many archaeological sites. In April 2019 the NPS will implement experimental vegetation removal treatments in Grand Canyon to increase aeolian sediment supply from HFE sandbars to several dunefields that host archaeological sites. GCMRC will monitor the outcome the vegetation treatments relative to future HFEs.

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BIG FLOOD, SMALL FLOOD, SPRING FLOOD, FALL FLOOD: HFE TIMING AFFECTS FOOD BASE RESPONSE?

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High-Flow Experiments (HFEs) are an important tool in river rehabilitation and restoration efforts worldwide. These floods have the potential to rehabilitate rivers by restoring important geomorphic processes, disadvantaging non-native species, and providing a life history cue vital to native species. HFEs have been released from Glen Canyon Dam on the Colorado River eight times since 1996. Of these eight HFEs, two have occurred in spring (April 1996 and March 2008) and six have occurred in fall (November of 2004, 2012, 2013, 2014, 2016, and 2018; see Grams and others, 2019, extended abstract, this volume).

Studies of the aquatic food base that fuels fish populations before and after the 1996 spring-timed HFE demonstrated invertebrate biomass recovered to pre-HFE levels within a month (Shannon and others, 2001). Additionally, food base samples collected from Grand Canyon in June 1996, roughly three months after the HFE, had some of the highest biomass values and highest diversity of invertebrates during the six years of monitoring preceding the HFE (Shannon and others, 2001). No food base monitoring occurred from 2002-2006, a period of years that included the 2004 fall-timed HFE.

From 2006-2009, monthly food base monitoring occurred in Glen Canyon and quarterly food base monitoring occurred in Grand Canyon. In Glen Canyon, the 2008 spring HFE enhanced the prey base by reducing biomass and cover of aquatic macrophytes, reducing the abundance of inedible New Zealand mudsnails that prefer macrophyte beds, and increasing the abundance of high-quality insect taxa (i.e., midges and blackflies) that prefer bare substrates (Figure 1; Cross and others, 2011). In Grand Canyon, the 2008 spring HFE did not appear to have any measurable effect on the food base but inferences were weak compared to Glen Canyon because only quarterly sampling occurred in Grand Canyon whereas monthly sampling occurred in Glen Canyon.

New approaches for food base monitoring were adopted in 2012 following review by a Protocol Evaluation Panel. These new approaches include use of drift sampling in Glen and Grand Canyon to monitor aquatic life stages of invertebrates and use of citizen science light trapping to monitor the adult, terrestrial life stages of aquatic insects throughout Grand Canyon. Preliminary trends in these new food base monitoring data are highly correlated with trends in fish condition and growth, indicating that these new food base monitoring data are a useful metric of food availability for fishes.

Since 2012, five fall HFEs have been tested (i.e., 2012, 2013, 2014, 2016, and 2018; see Grams and others, 2019, extended abstract, this volume). From 2012-2018, long-term trends in drift and light trap data from both Glen and Grand Canyon have been flat or negative (Figure 1; Kennedy and others, unpublished data). For example, the abundance of inedible New Zealand mudsnails in Glen Canyon drift samples has remained high since 2012 and has not declined following any of the fall HFEs. Similarly, the abundance of high-quality insect taxa in Glen Canyon drift samples has remained relatively low since 2012. In Grand Canyon, the abundance of larval midges captured in drift samples and the abundance of adult midges captured in light trap samples has been flat or declining since 2012 (Kennedy and others, unpublished data).

Inferences concerning the role of HFE timing can also be drawn from the published literature. For example, a 2017 synthesis of aquatic invertebrate response to flow alteration from 682 streams and rivers throughout the U.S. concluded that healthy invertebrate communities were present in streams and rivers where high flows occurred in spring whereas impaired invertebrate communities were present in streams and rivers where high flows were absent or did not occur in spring months (i.e., March, April, May; Carlisle and others, 2017).

Collectively, these food base studies and syntheses indicate that spring HFEs may enhance the food base while fall HFEs do not enhance the prey base. However, inferences concerning the beneficial effects of spring HFEs are relatively weak owing to infrequent testing of spring HFEs downstream of Glen Canyon Dam; additional testing of spring HFEs at Glen Canyon Dam would help reduce this uncertainty.

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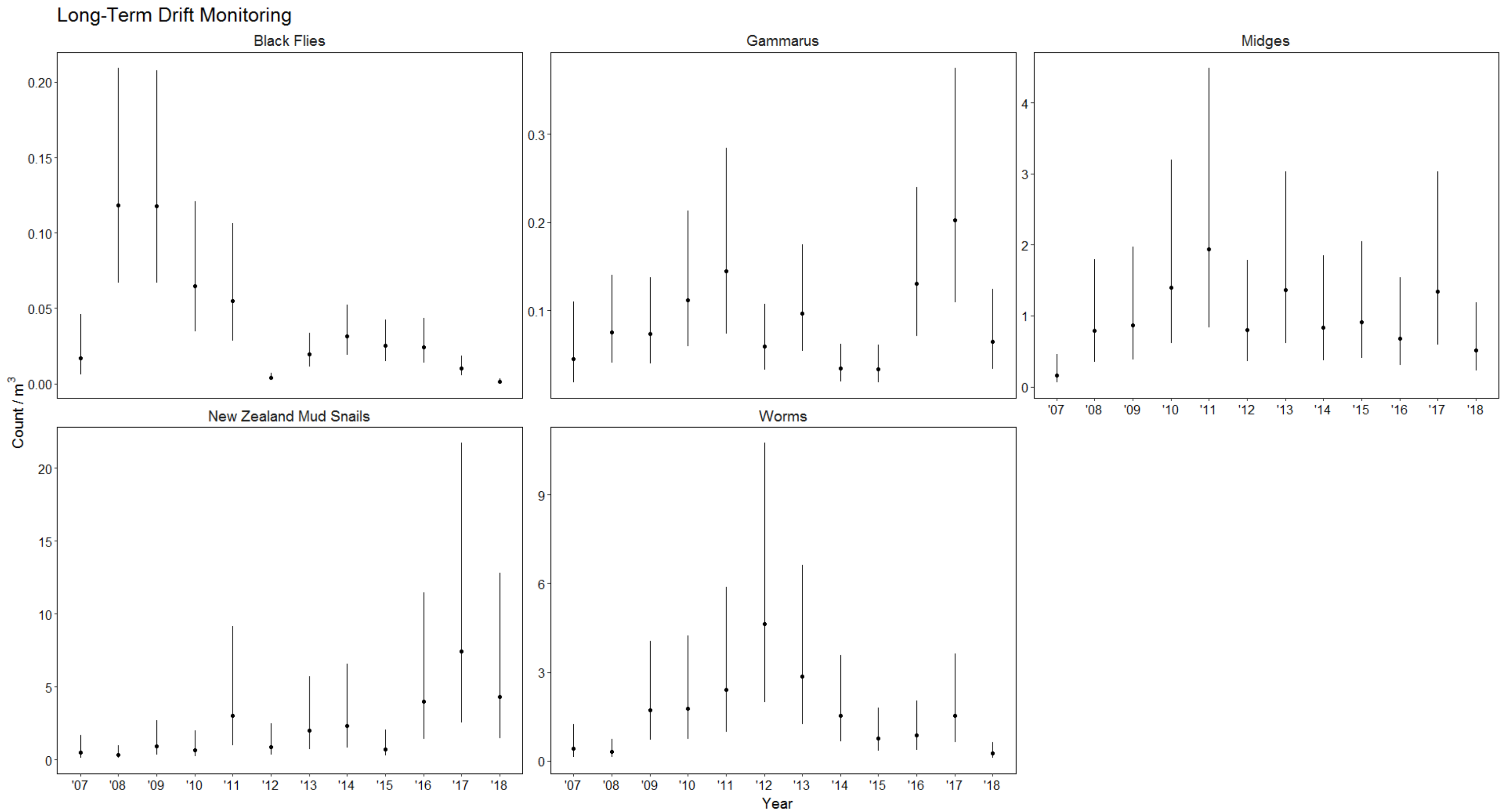

Figure 1. Yearly patterns in aquatic invertebrate drift in Glen Canyon, AZ for the five most common aquatic taxa. Note that the scale of the y-axis (drift concentration) differs by taxon.

EFFECTS OF HIGH-FLOW EXPERIMENTS ON WARM-WATER NATIVE AND NONNATIVE FISHES

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The harsh environmental conditions and extreme flooding that created Grand Canyon also shaped the unique native fish that evolved in the Colorado River. Native fish have evolved their physiology, morphology and behavior to withstand high flood events. Flooding has been shown to benefit spawning, survival and recruitment of juvenile native fishes in many southwestern rivers. Annual pre-dam flooding on the Colorado River was sometimes more than double the flows released during a typical High-Flow Experiment (HFE). It is therefore unlikely that the 3-4 days of high flow created by HFEs will have negative impacts on native fish directly. However, HFEs can cause dispersal of flood adapted non-native species like green sunfish that utilize floods to invade and colonize new environments. Continued efforts to reduce known populations of green sunfish that inhabit backwater ponds before conducting HFEs may be necessary to reduce risks of spreading invasive green sunfish downstream.

The effects of HFEs on Colorado River fishes can be assessed by evaluating the environmental conditions that are created both during and following an HFE. Immediate effects of an HFE are largely determined by channel morphology. In areas with a wide floodplain an HFE can create shallow flooded areas on the river margins, but in narrow canyon-bound areas an HFE typically will have little effect on fish habitat (Avery and others, 2015). More persistent effects of HFEs such as building of backwaters and changes to the food base can occur, but whether those impacts have population level effects for native fish is not well understood (Dodrill and others, 2016). Native fish do use backwaters, but backwaters that are formed during HFEs typically do not warm substantially (<0.2°C) or persist long enough to significantly increase growth rates of native fishes (Ross and Grams, 2013). Backwaters can aggregate nonnative species that prey on native fishes and individual predation rates in backwaters are higher than in the mainstem (Dodrill and others, 2016); however, population-level effects of backwaters created by HFEs on native fishes have not been established because of the limited number and temporary nature of the backwaters that are created.

Standardized, long-term monitoring of fishes in the Colorado River in Grand Canyon is currently used to evaluate the effects of HFEs on warm-water native and nonnative fish populations (Rogowski and Boyer, 2019). During the period from 2012-2018, abundance and distribution of native fishes in the Colorado River increased significantly (Figure 1) with large expansions of humpback chub (*Gila cypha*), particularly in the western portions of Grand Canyon (Figure 2, Van Haverbeke and others, 2017; Rogowski and others, 2018), along with reduced abundance of warm-water invasive fishes (Rogowski and Boyer, 2019). Although the exact cause for these changes in fish populations are unknown, it is likely related to warmer mainstem water temperatures and is unlikely related to recent HFEs for the reasons outlined above. The effects of HFEs on fish is dependent on the species that are present, the environmental conditions that are created, and the life stages of fish inhabiting the river at the time when the HFE occurs. This creates the need to periodically re-evaluate the effects of HFEs on fish as river conditions, seasonal timing of HFEs, and fish assemblages change.

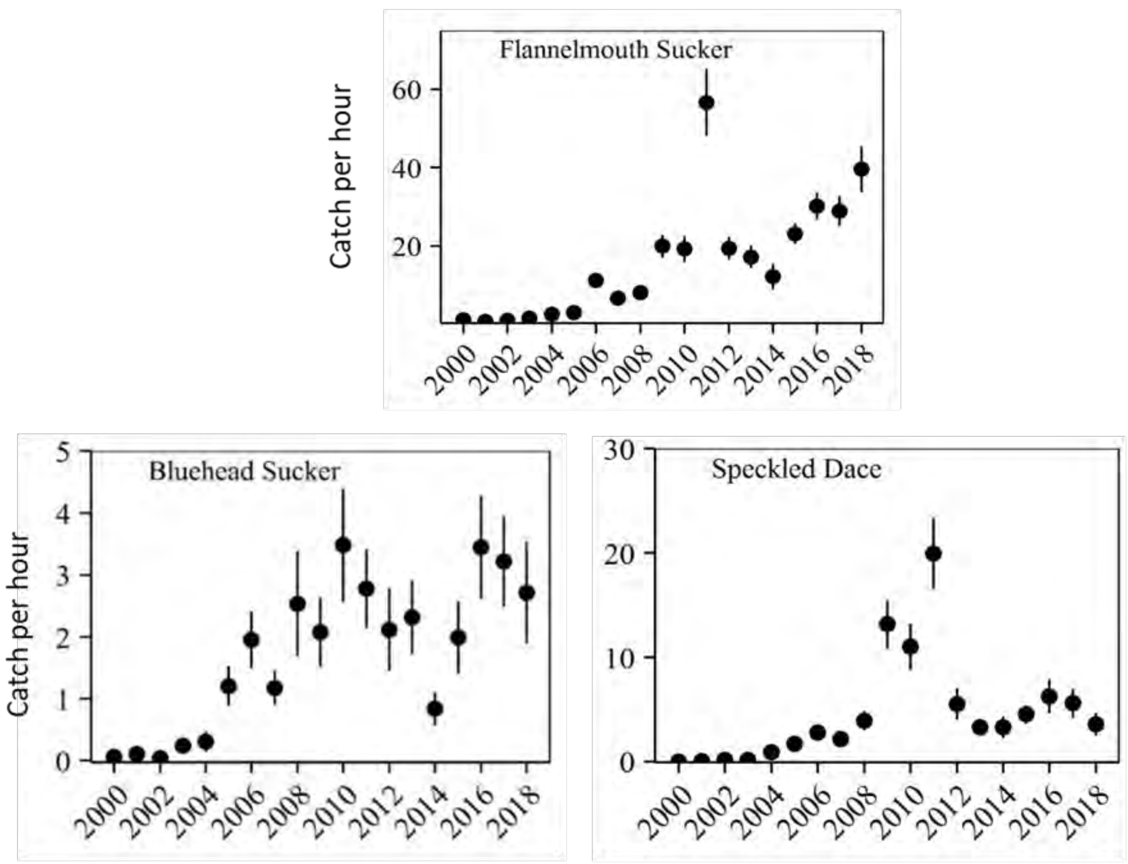

Figure 1. River-wide mean catch per unit effort (CPUE; fish/hour) for years 2000–2018, conducted by the Arizona Game and Fish Department in the Colorado River in Grand Canyon from Lees Ferry (RMI 0) to Pierce Ferry (River Mile (RMI) 279) for flannelmouth sucker, bluehead sucker, and speckled dace. The point is the mean and error bars represent 95% confidence intervals.

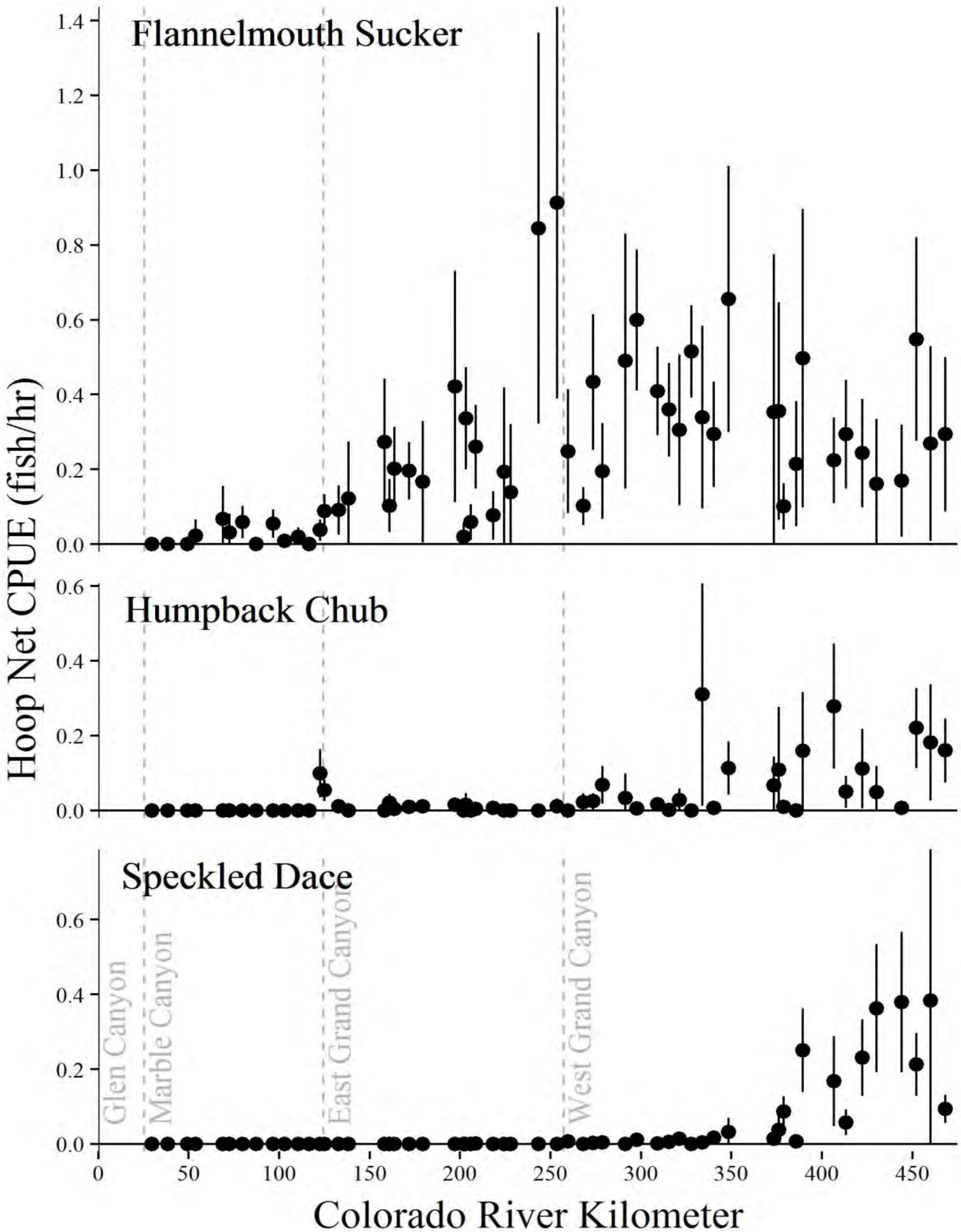

Figure 2. Hoop net Catch per Unit effort (CPUE; fish per hour) for 2016-2018 from standardized, long-term fish monitoring conducted by the Arizona Game and Fish Department in the Colorado River in Grand Canyon from Lees Ferry (RMI 0) to Pierce Ferry (RMI 279). Trends show increasing numbers of flannelmouth sucker, humpback chub and speckled dace in western Grand Canyon. Error bars represent 95% confidence intervals.

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EFFECTS OF HIGH-FLOW EVENTS (AND OTHER FACTORS) ON SALMONIDS

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Eight High-Flow Experiments (HFEs) have been released from Glen Canyon Dam since 1996 with two having occurred in the spring (i.e., April 1996 and March 2008) and the remaining six occurring in fall (i.e., November of 2004, 2012, 2013, 2014, 2016, and 2018). Here I attempt to synthesize understanding of the impacts of both types of HFEs on vital rates (growth, recruitment, movement, etc.) of rainbow and brown trout in Glen and Marble Canyons.

The two spring-timed HFEs have coincided with years of high rainbow trout recruitment in the Glen Canyon reach, and there are multiple lines of evidence suggesting that the HFE played a role in the high recruitment in 2008 (Korman and others, 2010; Cross and others, 2011). Nonetheless, it is unclear if spring HFEs would cause high recruitment in all years, given their limited replication and the lack of experimental design to separate effects of spring HFEs from other factors that might promote recruitment. For example, both spring HFEs occurred in years when Soluble Reactive Phosphorous (SRP) was increasing after having been low for a few years and rainbow trout recruitment and growth is positively correlated with in SRP. Furthermore, recruitment was extremely high in 2011 and coincident with further increases in SRP (and unusually high and steady flows) but there was no HFE preceding it. Conducting a spring HFE in a year when SRP was declining or low, as in 2014, could help to tease out the relative importance of these two hypothesized drivers.

It has also been hypothesized that fall HFEs may play a negative role in the dynamics of rainbow trout in the Glen Canyon reach. There has been more replication of fall HFEs, however a statistically significant impact on recruitment has not yet been identified and if one exists, it is likely to be small. While early fall HFEs (i.e., 2004, 2012-2014) coincided with low recruitment years, more recent years (including both fall HFE and non-fall HFE years) have coincided with moderate recruitment. Data from the Natal Origins project (U.S. Department of the Interior, 2014) and Trout Reproductive and Growth Demographics project (U.S. Department of the Interior, 2017) suggest that overwinter (post fall-HFE) growth may be lower in fall HFE years as compared to non-fall HFE years and this could conceivably affect population dynamics (Korman and others, unpublished data), however more years are required to confirm this pattern. As is the case for recruitment, multiple factors influence growth of rainbow trout in Glen Canyon including prey availability, water temperature, and the density of rainbow trout.

While rainbow trout are desired in the Glen Canyon reach, they are undesired in Marble Canyon, particularly near humpback chub aggregations at 30 mile and around the confluence with the Little Colorado River. Several relevant factors change between Glen and Marble Canyons. In Glen Canyon, macrophytes and New Zealand mudsnails are abundant and both are trophic dead-ends (i.e., primary production from macrophytes does not fuel production of invertebrates and by extension fish, and secondary production of New Zealand mudsnails does not fuel production of fish). Spring HFEs appear to reduce abundance of both thereby freeing up algae energy for other invertebrates that are actually eaten by rainbow trout. Fall HFEs, in contrast, export prey items at a time when light, and thus energy are becoming scarce, potentially negatively impacting rainbow trout growth during the winter interval. In addition, turbidity in Glen Canyon is almost always low. In Marble Canyon, New Zealand mudsnails and macrophytes are uncommon and the primary mechanism by which HFEs affect rainbow trout is likely through impacts on turbidity. In Marble Canyon increased turbidity is known, with high certainty, to limit rainbow trout foraging during parts of the year (Korman and others unpublished data; Dodrill and others unpublished data). In years of low turbidity (particularly during the winter and spring), such as years with fall HFEs or low tributary activity, rainbow trout have higher growth, survival and reproduction in Marble Canyon all the way down to the Little Colorado River (Korman and others, unpublished data); however, it is unclear how much of the decreased turbidity in Marble Canyon in some years is attributable to fall HFEs versus interannual variation in Paria sediment inputs.

Brown trout have been increasing in the Glen Canyon reach in recent years and are of concern to managers, because brown trout are highly predatory and have a greater per capita impact on humpback chub than rainbow trout (Yard and others, 2011; Runge and others, 2018). There is strong evidence to suggest that brown trout increased due to an immigration pulse in 2014 followed by increased fecundity in 2015 (Runge and others, 2018), and that the number of adult brown trout continued to increase in Glen Canyon in 2018 despite somewhat lowered recruitment of juveniles in the last few years. While the demographics are fairly refined, our understanding of causal mechanisms to explain these demographics is poor. Fall HFEs may have served as a cue for upstream migration and contributed to the immigration pulse, but such immigration pulses have not been observed in most fall HFE years. Furthermore, fall HFEs may have contributed to long-term trends in macrophyte cover, or some other aspect of the environment in Glen Canyon that is facilitating brown trout recruitment, however there is little evidence of a direct link between recruitment in fall versus non-fall HFE years (Runge and others, 2018). In short, we have a poor understanding of brown trout population dynamics and state variables (i.e., abundances).

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EFFECTS OF HIGH-FLOW EXPERIMENTS ON OTHER RESOURCES: RECREATION AND HYDROPOWER

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RECREATION

Glen Canyon National Recreation Area (GCNRA) and Grand Canyon National Park (GCNP) offer unique recreational opportunities. An objective in the Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS) is to maintain and improve the quality of recreational experiences (U.S. Department of the Interior, 2016). Some of the higher valued recreational activities include day-use rafting and angling in GCNRA and whitewater rafting in GCNP. The LTEMP EIS identified that Glen Canyon Dam (GCD) operations can affect the experience of day-use rafters and anglers in GCNRA and whitewater rafters in GCNP, including High-Flow Experiments (HFEs) (U.S. Department of the Interior, 2016).

The LTEMP EIS identified four recreation metrics in GCNRA and six recreation metrics in GCNP that can be used to monitor the recreational experience (U.S. Department of the Interior, 2016). These included a metric used to estimate the lost day-use rafting opportunities due to HFEs and a flow metric used to identify when recreational activities in GCNRA, specifically angling, are inaccessible. The most direct impact of HFEs in GCNRA are lost user-days. Visitors to GCNRA are unable to participate in day-use rafting during, and two days pre and post, HFEs. This is similar for angling in GCNRA as shoreline and motorized access become unavailable during HFEs. Unlike whitewater rafting in GCNP, rafting and angling in GCNRA are day-use, where many people participate in multiple, separate trips a year. Because there are substitute sites for these recreational activities (e.g., other tailwater fisheries in the region), the long-term impact of HFEs on participation of these recreation groups is uncertain.

There are also LTEMP EIS metrics used to establish guidelines for achieving a healthy, high-quality recreational rainbow trout fishery in GCNRA (U.S. Department of the Interior, 2016). The two metrics that reflect the quality of the rainbow trout fishery include catch rate per hour (age 2+ fish) and abundance of larger rainbow trout *(Oncorhynchus mykiss*) (greater than 16 inches in length) (U.S. Department of the Interior, 2016). While there is significant uncertainty in the effect of HFEs on rainbow trout recruitment and growth, fall HFEs are expected to have little to no impact on rainbow trout while spring HFEs may have a positive effect (Runge and others, 2018).

For GCNP, metrics used to monitor the recreational experience are focused on whitewater rafting. These metrics include a campsite area, navigational risk, river fluctuation, and time-off-river indexes. The impact of HFEs on whitewater rafting is primarily the increase in campsite area due to sandbar deposition during HFEs. In this case, whitewater rafters benefit when HFEs increase or maintain campsite area. Navigational risk, river fluctuation, and time-off-river impacts of HFEs in total are negligible over the course of the year (U.S. Department of the Interior, 2016). These metrics, for the vast majority of days throughout the year, are influenced by base operations which are independent of HFEs (U.S. Department of the Interior, 2016).

Recent studies by Grand Canyon Research and Monitoring Center have established that recreational values of angling and whitewater rafting in Glen and Grand Canyons have been consistent over the last 30 years (Neher and others, 2017). While economic values associated with whitewater rafting and angling are stable, the seasonal variation in recreational use and its associated value is of importance when evaluating the timing of HFEs (Bair and others, 2016). For example, fall and spring HFEs could have a significantly different impact on the use of campable area given that whitewater rafting occurs primarily in the summer months. Therefore, a systematic evaluation of recreational impacts of HFEs and the timing of recreational use would provide insight into the total recreational impact of HFEs.

HYDROPOWER

Glen Canyon Dam provides a relatively large amount of energy and firm capacity to the power system compared to other generating units. An objective in the LTEMP EIS is to maintain or increase the economic value of hydropower and minimize emissions, consistent with the sustainably of downstream resources (U.S. Department of the Interior, 2016). Flow experiments, including HFEs, impact the economic value of hydropower and power system emissions. The metrics used to monitor the impact GCD operations on hydropower include the economic value of hydropower generation and capacity. HFEs impact the economic value of hydropower generation by moving generation from on-peak hours to off-peak hours and by moving water through the bypass tubes.[1] The economic value of hydropower generation is reduced because off-peak generation could have otherwise been used to generate energy during on-peak hours, replacing the most expensive energy generation. Economic value is also reduced when water is moved through the bypass tubes during an HFE because no electricity is generated with that volume of water. There is no anticipated reduction in the value of capacity for 96-hours or less HFEs. High-Flow Experiments of 96-hours or less do not impact the volume of water released at GCD in August, the month with the highest electricity demand and used to determine capacity requirements. However, extended HFEs of greater than 96-hour duration

[1] The economic value of hydropower may also be impacted by HFEs through the reallocation of water volume across months. For example, during a 96-hour fall HFE water is moved from March and April to November and if prices of energy differ across these months the economic value of hydropower may be impacted.

would further reduce the economic value of hydropower generation and potentially have an impact on the value of hydropower capacity.

The total estimated economic costs for a single 96-hour fall HFE is approximately $1.62 million (U.S. Department of the Interior, 2016). This estimated economic cost is the same for a 96-hour spring HFE (U.S. Department of the Interior, 2016). However, a decrease in the difference between on-peak and off-peak energy prices, due to the integration of renewables and the decline in natural gas prices, has reduced the economic costs of recent 96-hour HFEs in the fall. Other considerations that could impact the total economic value of hydropower during flow experiments is the assessment of power system emissions. For example, hydropower replaces natural gas generation on-peak and coal-fired generation off-peak (U.S. Department of the Interior, 2016). In general, coal-fired generation produces at least twice the carbon dioxide, SO_2, and NO_x as natural gas generation for the same unit of energy generated (U.S. Department of the Interior, 2016). Therefore, consideration of the HFE impact to power system emissions, along with the economic value of hydropower generation and capacity, could improve the monitoring of HFEs at GCD.

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