RECLAMATION

Managing Water in the West

Sediment Analysis for Glen Canyon Dam High Flow Experiment Protocol Environmental Assessment

Upper Colorado Region, AZ

U.S. Department of the Interior
Bureau of Reclamation

December 2010

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Cover Photo: Colorado River upstream of Lees Ferry taken in June, 2010.

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Executive Summary

An environmental assessment (EA) is being produced by the Bureau of Reclamation's Upper Colorado (UC) Regional Office to determine the impact of high flow experiments (HFE) from Glen Canyon Dam on natural resources downstream. In order to determine impacts to sandbars and other resources downstream of Glen Canyon Dam, the approximated frequency, magnitude and duration of high flows is required. A sand budget model developed by U.S. Geological Survey (USGS) was modified to determine how many HFEs could occur based on estimated future dam releases, sediment input from the Paria River, and downstream sediment mass balance.

Based on previous scientific findings, the key criteria that determined the model decision making include maximizing flow magnitude to generate the largest possible sand concentrations and area of inundation, increasing the duration to keep sand concentrations elevated as long as there is available sand, and selecting the maximum HFE in an implementation month while maintaining a positive sand balance for the accounting period.

The modified model has multiple limitations including that sandbar building is not assessed in the model. The model only considers sand mass balance; it does not differentiate between sediment in the channel and sediment in the sandbars. Key input parameters to the modified sand budget model consist of release hydrographs and tributary inputs. Three 10-year release hydrographs were utilized based on simulations run by the Colorado River Simulation System (CRSS) model. Three tributary inputs were selected by analyzing the Paria River sand-load record. Thirteen options for HFEs were tested in the modified sand budget model ranging from a peak discharge of 45,000 ft^3/sec with peak duration of 96 hours to a peak discharge of 31,500 ft^3/sec with peak duration of 1 hour.

The modified sand budget model was used to simulate nine combinations of hydrology and tributary sediment traces. An HFE was selected by the model in 56% of the potential implementation windows for the nine traces simulated. Of these HFE's, 92% had a peak magnitude of 45,000 ft^3/sec whereas eight of the thirteen possible HFEs had a peak magnitude of 45,000 ft^3/sec. Typically HFEs occur in groups; 80% of the predicted HFEs had an HFE in the neighboring accounting periods. In the model, the occurrence of an HFE can be triggered by a certain level of sediment regardless of the hydrology because water is not considered limiting and can be reallocated within the month. For the nine traces, the average monthly Paria sand load that always resulted in an HFE was 500,000 metric tons per month.

Using previous literature, the HFEs recommended by the modified sand budget model will likely cause an increase in the sand volume above the 8,000 ft^3/sec water surface elevation. Some sediment will be eroded from the lower eddies, but this amount will be minimized based on previous tributary inputs ensuring the system is not depleted within the accounting period. The redistributed sand will erode in the months following the HFE and the rate will be dependent on dam releases and any new tributary inputs.

1 Introduction

An environmental assessment (EA) is being produced by Bureau of Reclamation's Upper Colorado (UC) Regional Office to determine the impact of high flow experiments (HFE) from Glen Canyon Dam on natural, cultural and socioeconomic resources downstream. The EA will consider impacts over a ten (10) year period, 2011-2020. Sediment and sandbars along the Colorado River are important downstream resources in Grand Canyon National Park and have linkages to recreation, aquatic and terrestrial habitat, and cultural resources.

In order to determine impacts to sandbars downstream of Glen Canyon Dam, the approximated frequency, magnitude and duration of high flows is required. A sand budget model developed by U.S. Geological Survey (USGS) was modified to determine how many HFEs could occur based on estimated future dam releases. In addition, the impacts to sediment and sandbars are assessed for a variety of HFEs over a 10-year period. This analysis includes approximately 77 river miles from Glen Canyon Dam to the Little Colorado River.

1.1 Objectives

The purpose of this analysis is to estimate the frequency, magnitude, and duration of high flows that can be implemented to maximize potential for sandbar building with the available sand supply. The value of sand in the ecosystem for purposes other than sandbar building was not considered. Once the high flows have been estimated, a qualitative assessment of sandbar response is provided. Specific questions are:

1. How many HFEs might occur in the next 10 years (represented as 2010 through 2019)?
2. What is the expected magnitude and duration of high flows?
3. What are the limitations and assumptions of the HFE analysis?
4. Using the predicted HFEs, what is the qualitative assessment of sandbar effects over the next 10 years based on currently published literature?

2 Methods

A sand budget numerical model that tracks the storage and transport of sand in the Colorado River below Glen Canyon Dam has recently been developed by USGS (Wright et. al. 2010). The model uses empirically based rating curves for specific particle sizes. It computes the sand budget in three reaches:

1) upper Marble Canyon from Lees Ferry and Paria River confluence (River Mile (RM) 0) to RM 30,
2) lower Marble Canyon from RM 30 to Little Colorado River (RM61), and
3) eastern Grand Canyon from Little Colorado River to Phantom Ranch (RM 87) as shown in Figure 1.

The model was calibrated and validated on historical sediment and discharge information from September 2002 to March 2009 that included the 2004 and 2008 high flow experiments. Several output data are provided to the user including mass balance of sand in each of the three reaches over time, thickness of the bed and D_{50} of the bed material in each reach, and the suspended sediment D_{50} and concentration in each reach.

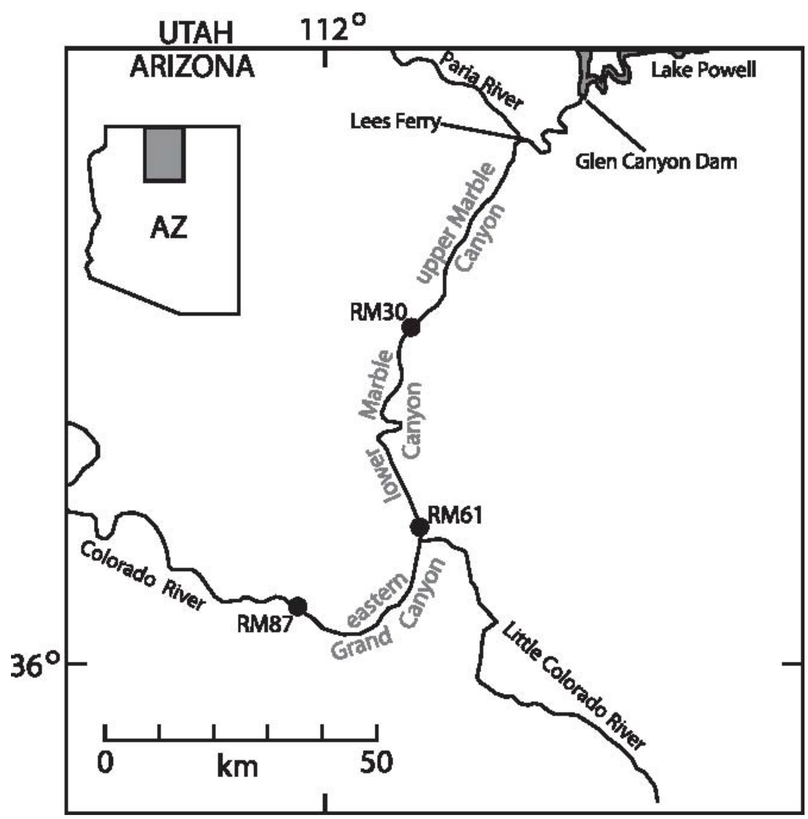


Figure 1. Sand budget model reaches (from Wright et al. 2010)

For the Environmental Assessment (EA), the sand budget model was combined with decision criteria on whether or not to conduct HFEs and then applied to help determine how many HFEs could hypothetically occur in the next 10 years given the decision criteria.

2.1 Model Decision Criteria

The decision to develop the model framework is predicated on the finding that conducting an HFE under sand enriched conditions has the potential to build sandbars repeatedly. "*Three definitive conclusions that have important implications for designing future sediment-management strategies can be drawn from these studies:*

1) *HFEs are effective at building sandbars by transferring sand from the channel bed to sandbars along the channel margins*
2) *HFEs conducted soon after tributary-derived sand has accumulated on the channel bed are more effective at building sandbars, and less likely to result in erosion of sand stored on the channel bed and in sandbars prior to the tributary inputs, compared to HFEs conducted when sand in the mainstem is depleted*
3) *Sandbars tend to erode quickly in the weeks and months following HFEs, depending on flow releases from the dam as well as ongoing tributary sand supply*" (Wright and Kennedy, in press).

Based on these findings, the key criteria that determined the model decision making include:

- Sandbar building potential is greatest by generating the greatest possible sand concentrations and largest possible areas of inundation, both of which are maximized by increasing flow magnitude.
- Sandbar building occurs as long as elevated sand concentrations are maintained and there is still space available to deposit sand; thus high flows should be of as long a duration as can be maintained with available sand.
- For each October-November and March-April HFE implementation months, the maximum HFE that can be conducted with the available sand supply is calculated iteratively by determining the highest ranking HFE that will not result in a negative sand balance for the accounting period.

From the findings and subsequent model decision making criteria, the model framework was created to ensure that an HFE would only be conducted under sand enriched conditions in an accounting period. Therefore, the sand balance in any one accounting period must be positive for an HFE to occur. In addition, multiple HFEs (maximum of two) can be conducted in a year if conditions warrant. This potentially compensates for the erosion that will inevitably occur between sandbar building/flood events.

The framework of the model is outlined below:

1. The sand balance at the beginning of the sediment year, July 1st is the starting point for the fall accounting period (July 1st to November 30th).
2. As sand is supplied from the Paria River or ungaged tributaries and exported downstream, the model keeps track of the cumulative sand balance in the accounting period for the sum of upper and lower Marble Canyon (reaches 1 and 2).
3. On November 1st the model determines whether an HFE can be implemented. The decision is based solely on the cumulative sand balance at the end of the accounting period.
    a. The model runs through the list of possible HFEs in the order provided.
    b. For each HFE, it inserts the HFE hydrograph on the 1st of the month, calculates steady flow for the remainder of the month so the amount of additional water required for the HFE is provided from the HFE month, and determines if the cumulative sand balance is positive on November 30th.
        i. If the cumulative sand balance is positive, the HFE is selected, and the model moves to the next accounting period.
        ii. If the cumulative sand balance is negative, the next HFE in the list is tested.
        iii. If the last HFE in the list produces a negative cumulative sand balance, the model will not conduct an HFE and moves to the next accounting period.
4. The sand balance on December 1st is the starting point for the spring accounting period (December 1st to June 30th).
5. The model repeats steps 2 and 3 for the next accounting period using April 1st instead of November 1st.
6. The model repeats steps 1 through 5 for the next nine years of interest.

A more detailed flow chart of the modeling process is shown in Figure 2. This framework is for the modeling protocol only. In practice the implementation protocol will be different and will potentially include decision points on October 1st and March 1st in addition to November 1st and April 1st so that there is sufficient time for the decision process.

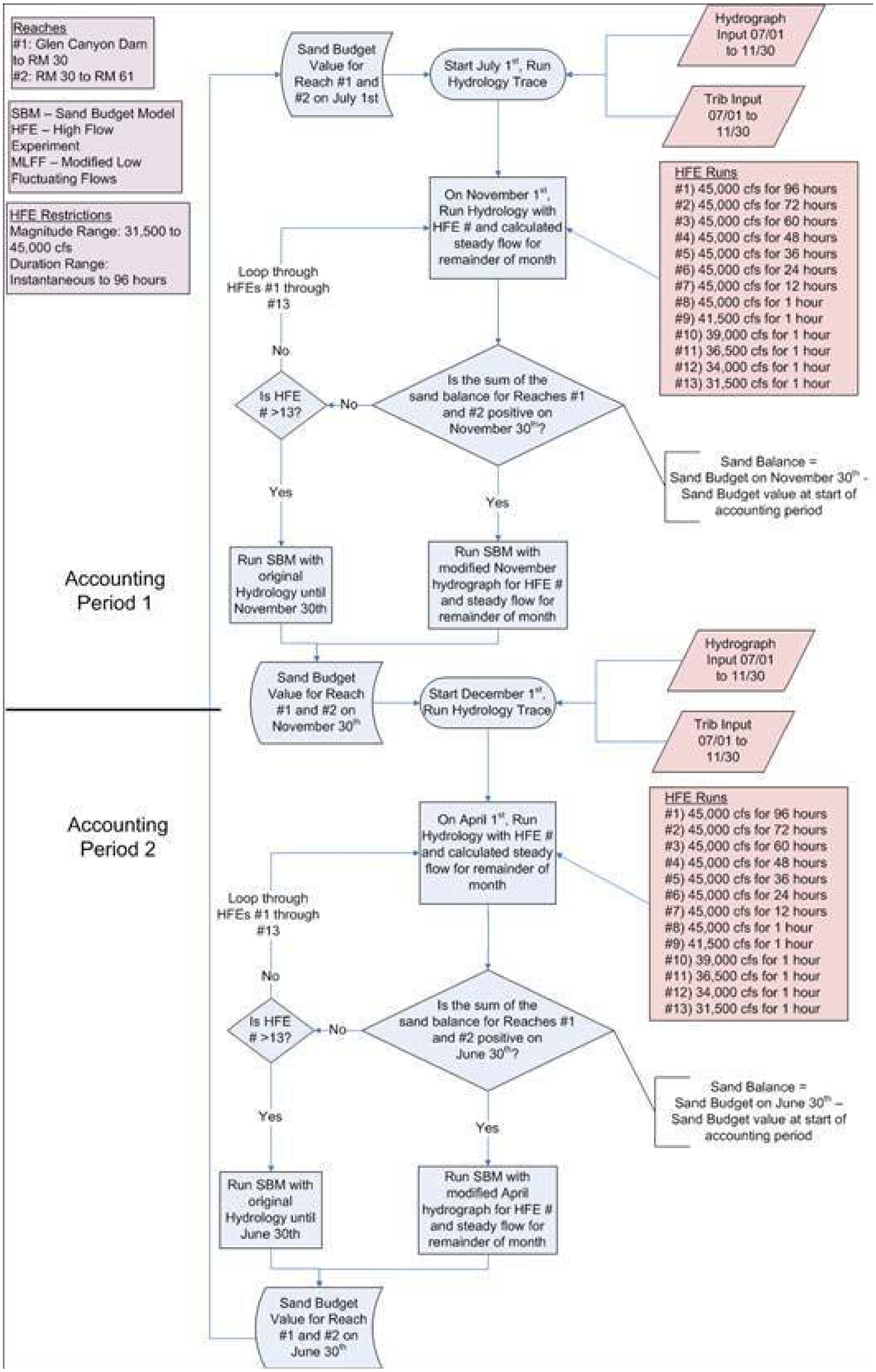


Figure 2. Detailed flow chart of modified sand budget model framework.

2.2 Model Assumptions and Limitations

The original sand budget numerical model (Wright et al. 2010) can be implemented for a variety of uses; however there are limitations due to the empiricism and simplifications made in the model. In summary, the model limitations are:

- The model parameters' coefficients are specific to the study reach (Colorado River below Glen Canyon Dam).
- The model does not capture effects of the pool-rapid-eddy morphology on sediment transport.
  - The model does not distinguish between sand on the main channel bed, eddies, and within the sandbars.
- The model doesn't account for changes in the area of sand covering the bed at a given time.
- The model cannot capture rapid changes in bed particle size and suspended-sand concentration.
  - The model cannot accurately capture changes due to tributary flooding.
- The model cannot capture particle size changes in relation to elevation. It is assumed that the sand is completely mixed.
  - The model does not include bed armoring effects.

In addition to the limitations of the sand budget model, there are also boundaries to the applicability and uses of the modified sand budget model. These limitations are described in the following sections.

2.2.1 General Limitations

- The model does not include any stakeholder/cooperating agency input which might modify or cancel a scheduled HFE. In addition the model does not incorporate any factors other than sand balance such as past HFE response, present sandbar volume, habitat conditions, cultural resources, etc.
- All 10-year simulations are assumed to be "perfect knowledge" of the future. Therefore, the model uses information in future months to make decisions in the current month.

2.2.2 Sediment Limitations

- Sandbar building is not assessed in the model. The model only considers sand mass balance; it does not differentiate between sediment in the channel and sediment in the sandbars. Based on monitoring, floods have been shown to transfer sand from the channel to the bars.
- The sand transport at the upstream boundary (Glen Canyon Dam) is zero.
- Flow from the Paria River is ignored; only the sediment inputs are used.
- Sand from the Paria River is input as average monthly loads and does not include any affects related to the magnitude and intensity of tributary flooding.

- To account for ungaged tributaries in upper Marble Canyon, the Paria River sediment inputs are increased by 10%.
- The model does not include any input from the Little Colorado River because they occur at the downstream end of Marble Canyon. Therefore only results from reaches 1 and 2 are considered in the HFE decision.
- The modified sand budget model provides the predicted sand balance. In practice, comparisions of the observed and predicted sand balances should be monitored.

2.2.3 Discharge Limitations

- The model only attempts a discrete number of HFE options. In reality, a wide range of HFE flow magnitudes and durations could be implemented.
- The model only allows an HFE to be implemented starting on April 1st and/or November 1st of a given water year. In practice, HFEs could occur on any day in the months of October-November or March-April as specified in the Environmental Assessment.
- The model is not able to simulate Modified Low Fluctuating Flows (MLFF) powerplant releases during the remainder of the month that an HFE is conducted. If an HFE is conducted, the flow in the remainder of the implementation month is assumed to be steady flow. In practice the remainder of the implementation month may have fluctuating flow.
- For the purpose of the simulation, the water volume used by each HFE is accommodated by adjustment to the releases for the remainder of the implementation month; in practice, the flow release volume also could be accommodated by adjustment to the monthly release volumes for the remainder of the water year.

2.3 Model Input

Key input parameters to the modified sand budget model consist of release hydrographs and tributary inputs.

2.3.1 Release Hydrographs

The Glen Canyon Dam release hydrographs were based on simulations run in Colorado River Simulation System (CRSS) model by Grantz and Patno, 2010. The operation of Lake Powell and Lake Mead in the CRSS modeling is pursuant to the December 2007 Record of Decision on Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations of Lake Powell and Lake Mead (Interim Guidelines), which includes the equalization operational tier. Upper Basin depletions come from the new (2007) Upper Colorado River Commission (UCRC) depletion schedule. The new Intentionally Created Storage (ICS) assumptions used in the bi-national modeling effort and in the official January 2010 CRSS run were also used.

To produce the traces, 500 simulations were run with the nonparametric paleo-conditioned (NPC) inflow hydrology. Based on a statistical analysis of the ranked average annual inflow volumes from 2010-2019, five dry, five moderate, and five wet traces were selected. The dry traces were closest to the 10% non-exceedance, moderate traces closest to 50% non-exceeedance, and wet traces closest to 90% non-exceedance. The Glen Canyon Dam annual releases corresponding to the 15 NPC inflow hydrologies were evaluated by visual inspection to select the traces with the greatest variability, the least amount of trend and eliminate those with step-functions. A wet, moderate and dry trace that maintained the consecutive ten-year duration was selected (Grantz and Patno, 2010).

CRSS distributes the Glen Canyon Dam annual release volumes on a monthly basis pursuant to rules consistent in the detailed criteria and operating plans contained in the 1996 Glen Canyon Dam Record of Decision (1996 ROD). This operation criteria is referred to in the 1996 ROD as MLFF. MLFF operating criteria exist for both daily and hourly operations at Glen Canyon Dam. The traces were disaggregated into hourly releases while maintaining the operational requirements of the MLFF operating criteria. Figure 3 shows the yearly volumes for each trace.

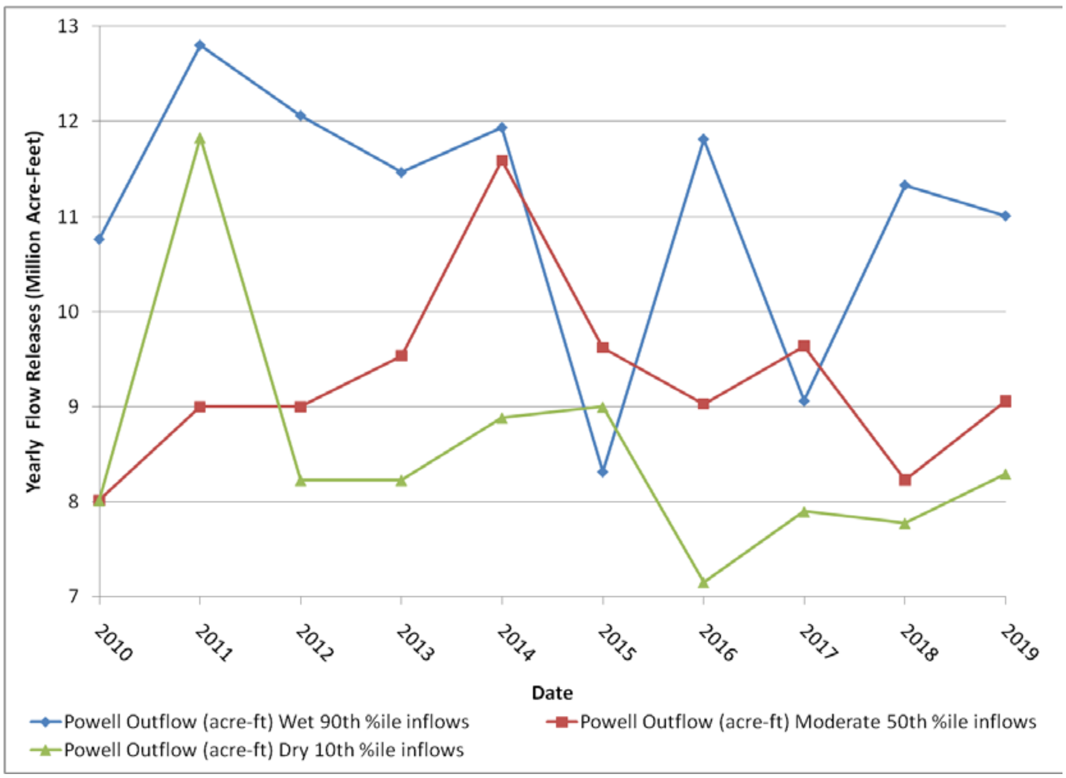


Figure 3. Yearly volumes for three Glen Canyon Dam release traces.

The Colorado River Flow, Stage, and Sediment (CRFSS) model has a reach-averaged one-dimensional, unsteady-flow model component. This component was used to route the three hydrology traces to calculate the hydrographs at RM 31, RM 60, and RM 87.3 to generate input for the modified sand budget model. The CRFSS model uses average channel geometry based on previously measured cross sections in Marble and Grand Canyons (Wiele and Griffin 1996, Wiele and Smith 1997).

In addition to routing the hydrology traces, the CRFSS model was also used to route the HFE hydrographs. Thirteen options for HFEs were tested in the modified sand budget model ranging from a peak discharge of 45,000 ft^3/sec with peak duration of 96 hours to a peak discharge of 31,500 ft^3/sec with a peak duration of 1 hour.

Table 1 shows the list of HFE options. The options were chosen to 1) maximize the peak discharge, 2) decrease the peak duration and 3) then decrease the peak discharge.

Table 1. List of possible HFEs tested by the modified sand budget model in order of preference.

HFE No.	**Peak Magnitude (ft^3/sec)**	**Peak Duration (hrs)**
1	45,000	96
2	45,000	72
3	45,000	60
4	45,000	48
5	45,000	36
6	45,000	24
7	45,000	12
8	45,000	1
9	41,500	1
10	39,000	1
11	36,500	1
12	34,000	1
13	31,500	1

Each HFE has an upramp rate of 4,000 ft^3/sec/hour and a downramp rate of 1,500 ft^3/sec/hour to follow MLFF criteria. Figure 4 shows an example of the dam release hydrograph (blue color) with the CRFSS generated hydrographs at RM 31 and RM 60. There is a lag time in the peak duration; however there is no attenuation of the peak magnitude.

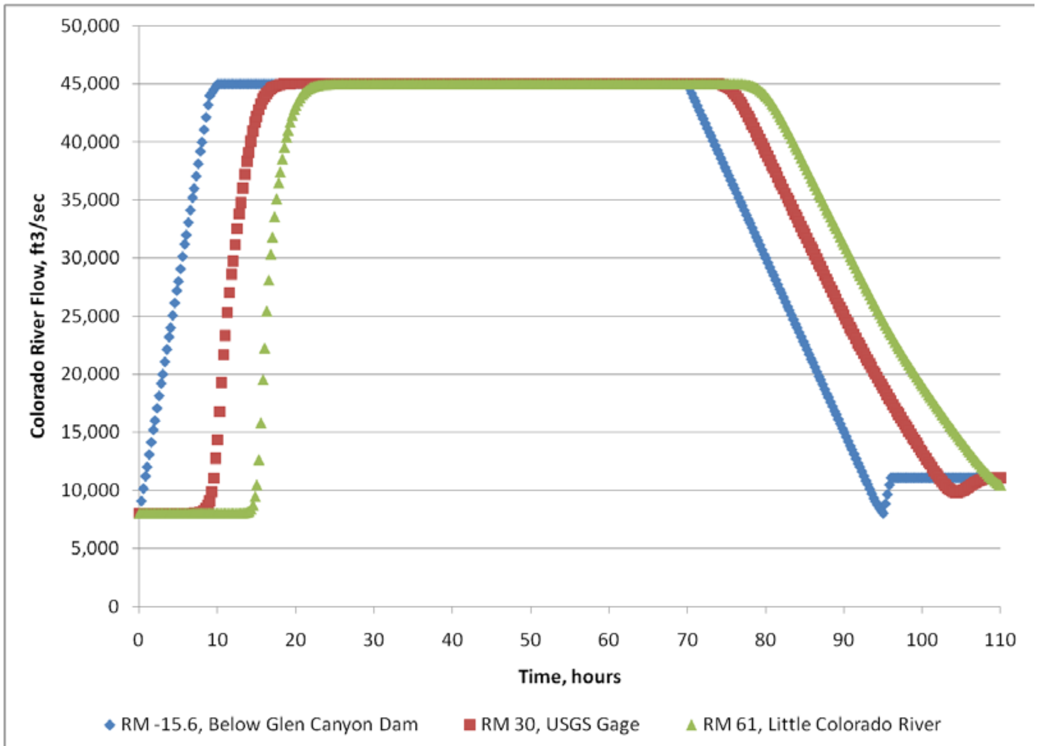


Figure 4. Flow hydrographs for HFE 3 (45,000 ft^3/sec for 60 hours) at RM -15.6, RM 30, and RM 61.

2.3.2 Tributary Inputs

The tributary inputs were developed by analyzing the Paria River sand-load record provided by USGS Grand Canyon Monitoring and Research Center (David Topping, U.S. Geological Survey, unpub. data) using a stochastic method. A forward looking ten-year (calendar year) moving average was calculated and then ranked. Figure 5 shows the results of the ten-year moving average.

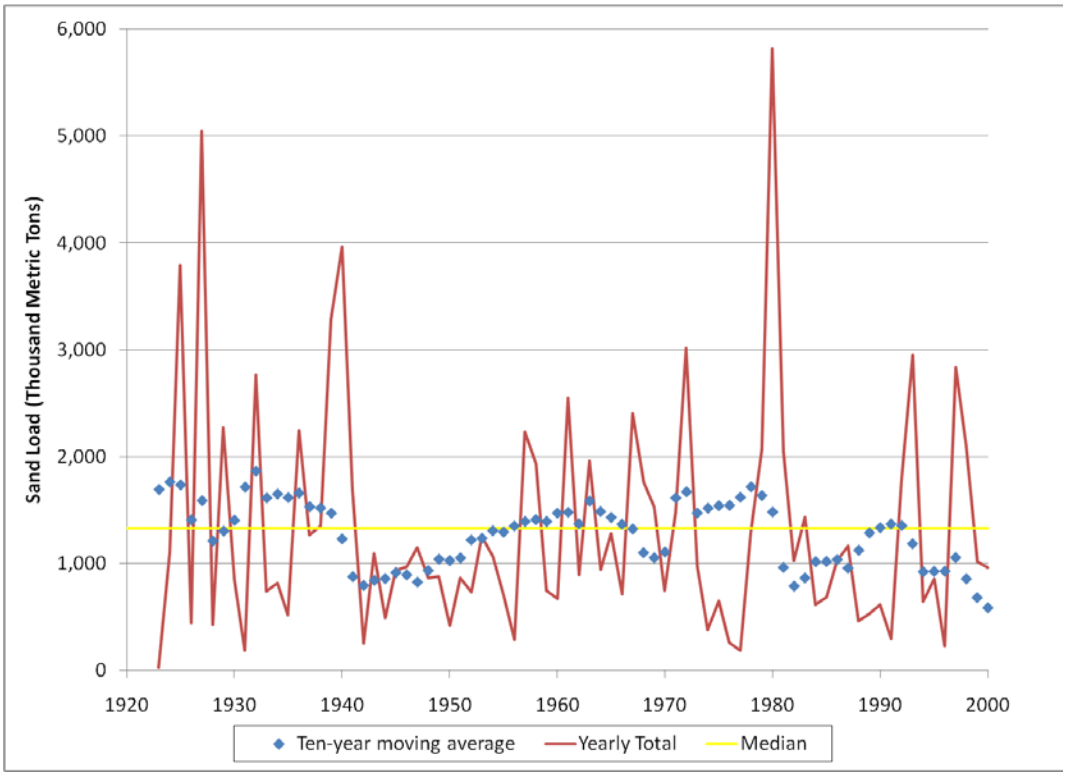
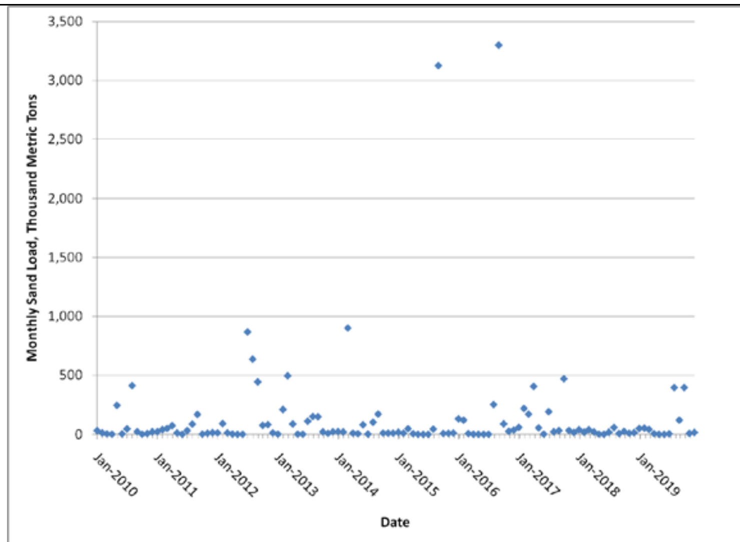


Figure 5. Yearly Paria River sand loads with calculated ten-year moving average.

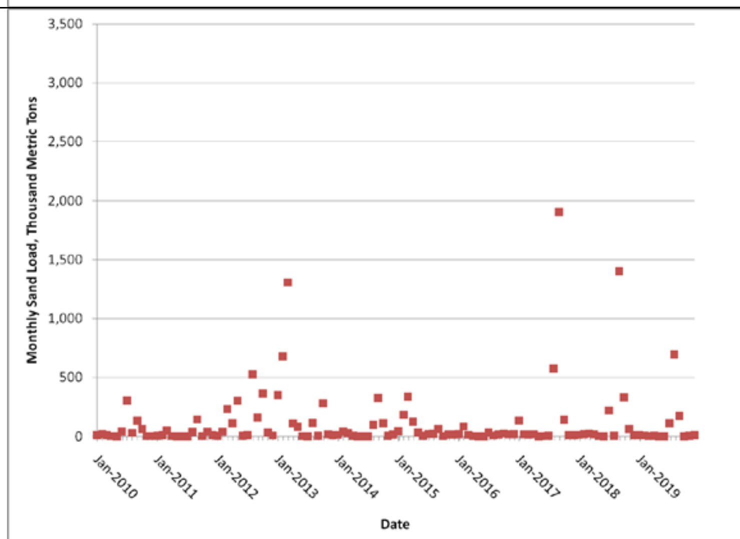
Three ten-year historical traces were selected from the ranked ten-year moving averages. 1983-1992 was selected as the 10% non-exceedance or low sediment trace. The 50% non-exceedance or moderate sediment trace selected was the sediment data from 1990-1999. The 90% non-exceedance or high sediment trace selected was from 1934-1943. The monthly sand loads for each trace are shown in Figure 6.

For each trace the monthly load was divided into 15 minute time step values to meet the sand budget model input requirements. Using an average monthly load rather than instantaneous sediment data does not take into account the effects of short duration tributary flooding. The total monthly load of sediment is valid and the simplification is assumed to not impact the results since the accumulation periods are over multiple months.

a) High Sediment Monthly Load Trace



b) Moderate Sediment Monthly Load Trace



c) Low Sediment Monthly Load Trace

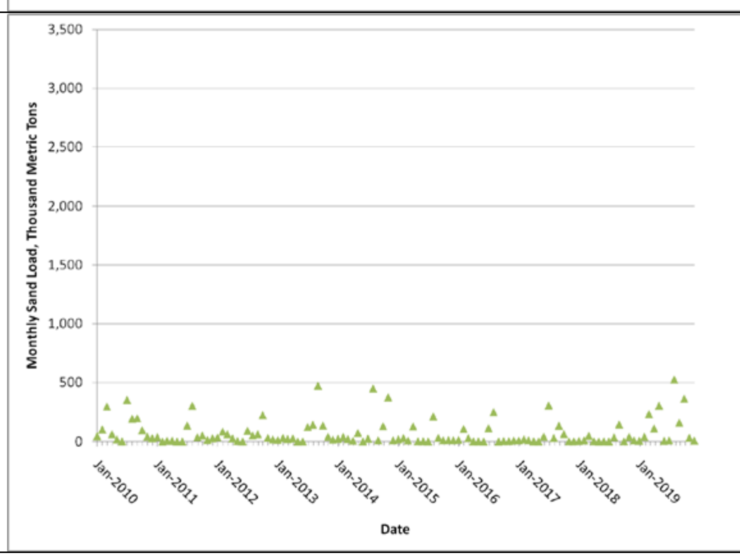


Figure 6. Total monthly sediment loads for the low, moderate, and high Paria River sediment traces.

2.3.3 Antecedent Conditions

The transport relation parameters' values, developed by Wright et. al. 2010, were unchanged for the modified sand budget model. The sand thickness, bed material gradation, and particles size distribution used are shown in Table 2. These values represent the March 2009 conditions (end of the validation simulation for the sand budget model) and were previously developed for simulations completed by Wright and Grams (2010).

Table 2. Initial bed and sediment conditions for the sand budget model reaches.

	Upper Marble Canyon	**Lower Marble Canyon**	**Eastern Grand Canyon**
Bed thickness (m)	0.45	0.48	0.56
Bed D_{50} (mm)	0.35	0.32	0.30
Particle size distribution standard deviation	2.0	2.0	2.0

2.3.4 Simulations

The modified sand budget model was used to simulate nine combinations of hydrology and tributary sediment traces shown in Table 3.

Table 3. Modified sand budget model simulations completed.

Hydrology input	**Tributary input**
10% hydrology trace	10% tributary sand supply 50% tributary sand supply 90% tributary sand supply
50% hydrology trace	10% tributary sand supply 50% tributary sand supply 90% tributary sand supply
90% hydrology trace	10% tributary sand supply 50% tributary sand supply 90% tributary sand supply

3 Results and Discussion

3.1 Modified Sand Budget Modeling

The model outputs include the number of HFEs that would occur during each ten-year simulation as well as what HFE peak flow and duration were selected. The amount of flow to be reallocated based on the HFE peak and duration is also calculated. Although nine simulations were completed, this section focuses on the moderate hydrology coupled with the moderate sediment simulation. Appendix A has the results of all nine simulations. It should be noted that the hydrology and sediment traces are all predictions of what may happen. It is unlikely that the actual hydrology and sediment conditions will exactly match any of the scenarios tested, but the range of simulations should cover the range of likely results.

The different traces do not have an equal probability of occurring; however there are some general trends that can be seen in looking at the entire set. For the nine traces, there were 180 opportunities for an HFE to occur. 100 of 180 HFEs were selected in the modeling or 56% of the time an HFE was selected. Of these HFE’s, 92% had a peak magnitude of 45,000 ft^3/sec. The HFE that was selected most frequently had a peak magnitude of 45,000 ft^3/sec for 96 hours. Typically HFEs occur in groups; 80% of the HFEs had at least one other HFE in a neighboring accounting period.

The nine traces produce more variability than the moderate hydrology, moderate sediment trace. Table 4 displays the HFEs selected by the model to be conducted with the moderate hydrology, moderate sediment trace. For this trace, there were no HFEs selected with a peak magnitude less than 45,000 ft^3/sec. However, the peak discharge durations varied from 1 hour to 96 hours. HFEs occur in both April and November. Some years have two HFEs, while some years do not have any HFEs. The maximum length without an HFE is 18 months. There is one period where there are four consecutive HFEs. The amount of water required to be reallocated in this trace varied from 45,000 to 326,000 acre-feet.

Table 4. HFEs to be conducted for the moderate hydrology, moderate sediment trace.

Month of Potential HFE	HFE No.	Peak Magnitude (ft^3/sec)	Peak Duration (hrs)
4/1/2010			
11/1/2010	6	45,000	24
4/1/2011			
11/1/2011			
4/1/2012	2	45,000	72
11/1/2012	2	45,000	72
4/1/2013	1	45,000	96
11/1/2013	8	45,000	1
4/1/2014			
11/1/2014			
4/1/2015	1	45,000	96
11/1/2015			
4/1/2016	8	45,000	1
11/1/2016			
4/1/2017			
11/1/2017	1	45,000	96
4/1/2018			
11/1/2018	1	45,000	96
4/21/2019			
11/1/2019	6	45,000	24

Based on the model results, the occurrence of an HFE can be triggered by a certain level of sediment regardless of the hydrology. The average monthly Paria sand load that always results in an HFE was 500,000 metric tons. This may not be a correct value under all circumstances, but was valid for the nine traces simulated in the model. Figure 7 shows the average daily dam releases and the sand load with the HFE months marked for the moderate hydrology, moderate sediment trace. When the sand supply rate is below 500,000 metric tons per month, an HFE may or may not occur depending on the overall sand balance and the hydrology. For example, the September, 2011 monthly load is 143,000 metric tons per month and an HFE is not selected to occur in November, 2011. However in February, 2016 the monthly load is 82,000 metric tons per month and an HFE is selected to occur in April, 2016. The upstream sediment supply rate can override the hydrology and antecedent conditions in the modeling traces if it was larger than 500,000 metric tons, otherwise the other variables play a more significant role.

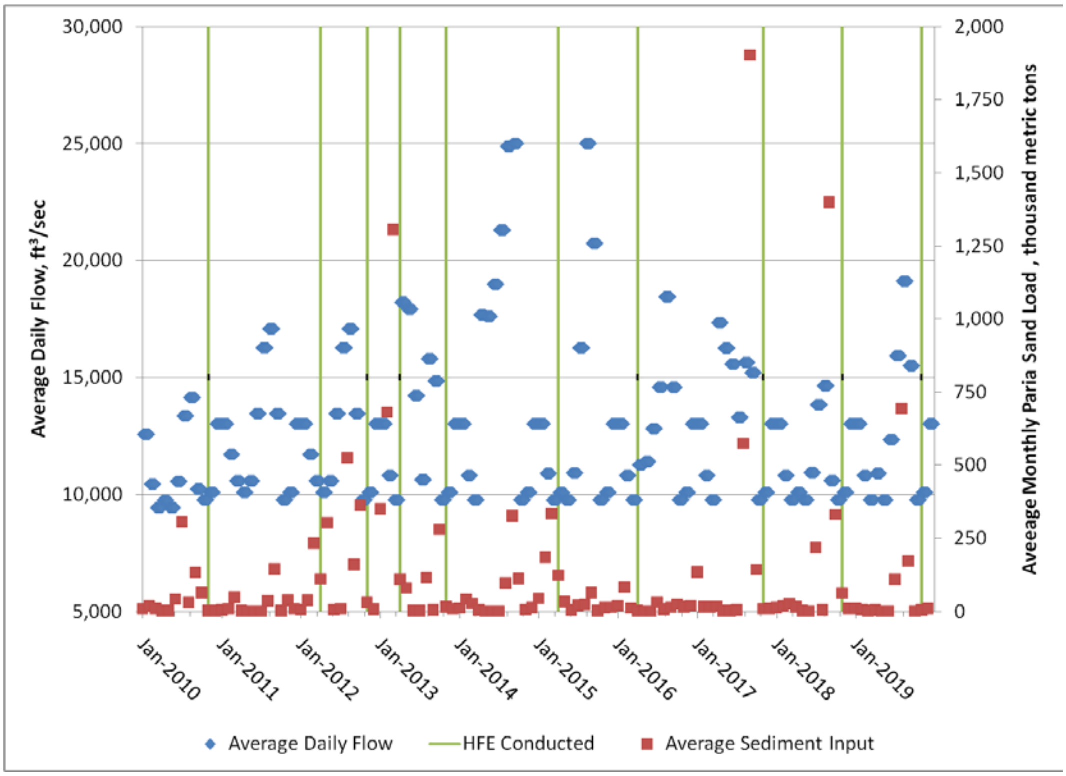


Figure 7. Average daily flow and average monthly sand loads for the moderate hydrology, moderate sediment trace with the HFEs resulting from the modified sand budget model.

Figure 8 tracks the cumulative sand balance throughout the modeling timeframe. The starting point, or zero, is the amount of sediment in the system on January 1, 2010. This is an arbitrary starting condition and is not meant to represent an optimal, average or target amount of sand in the system. Rather, it is a point of reference for the modeling. Since the modeling only considers the sand balance within each individual accounting period and resets at the beginning of each accounting period, this starting condition does not influence whether an HFE is conducted or not for any period, other than from January, 2010 through June, 2010. An HFE will be scheduled as long as there is a positive sand balance within the accounting period even if the cumulative sand balance, as displayed in Figure 8, is negative.

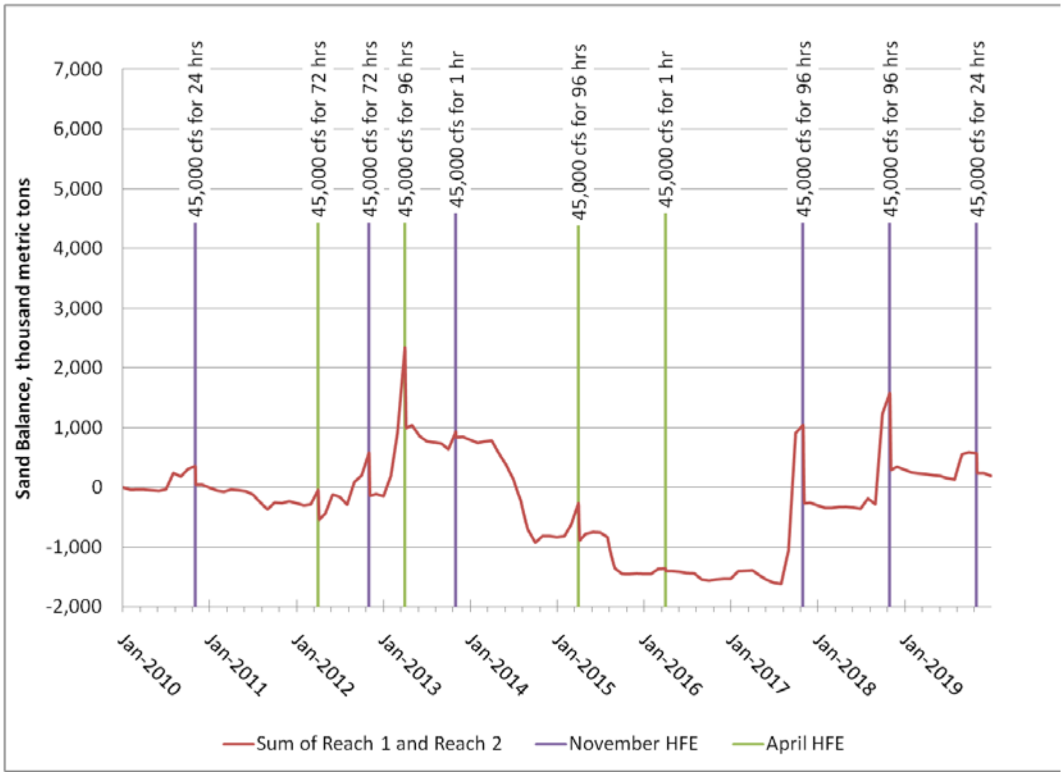


Figure 8. The cumulative sand balance (sum of Reach 1 and Reach 2) for the moderate hydrology, moderate sediment trace with the HFEs resulting from the modified sand budget model.

One of the concerns with conducting multiple HFEs, is the overall mass sand budget. For the moderate hydrology, moderate sediment trace, the ten-year overall sand budget increases by 99,000 metric tons. Of the nine traces simulated, five are negative and four are positive. The goal is to utilize the sediment when it enters the system to build sandbars, but not to drive the entire system into a large sediment deficit through the use of HFEs. It was possible to accomplish this goal in all the simulated traces.

It is important to realize that sand is being transported downstream and exported out of each of the reaches whether an HFE is conducted or not. Topping et al. (2000) discussed that in the pre-dam era, sediment was being conveyed or eroded when flows were over 8,800 ft^3/sec. The majority of times during MLFF, dam releases are over 8,800 ft^3/sec. The effects of regular dam releases without an HFE can be seen in Figure 8 between January, 2014 and January, 2015. No HFE was selected to occur in this year, but the sand balance decreased 1,630,700 metric tons. In addition, there were not many tributary inputs during this time (Figure 7).

Since sand is being exported whether or not an HFE occurs, it is still important to utilize “new” tributary sand when possible even if the overall sand balance is negative. This ensures that sand is moved to higher elevations before downstream transport. The April 2015 HFE is a good example of when this occurs. In March, 2015 the average monthly sand input is 335,000 metric tons. Although the overall sand balance is negative, an HFE is scheduled to utilize the recent input sand and relocate the sand to higher elevations.

3.2 Qualitative Sandbar Assessment

The model only considers sand mass balance; it does not differentiate between sediment in the channel and sediment in the sandbars. However, anticipated sandbar response to an HFE can be concluded from the literature available on previous high flows. To date, there have been three high-flow experiments as well as three habitat-maintenance flows, which can be considered smaller discharge high-flow experiments. A quick summary of the high-flow experiments is displayed in Table 5 and described below.

Table 5. Previously conducted high flow experiment parameters.

Date	Peak Magnitude (ft^3/sec)	Peak Duration (hr)
March-April, 1996	45,000	168
November, 1997	30,700	48
May, 2000	30,700	72
September, 2000	30,700	96
November, 2004	42,000	60
March, 2008	42,500	60

The 1996 HFE was conducted without a recent tributary input. The HFE resulted in increases to sand volume at elevations around the 25,000 ft^3/sec water surface elevation and scour to lower elevation eddies. "*Results from the 1996 controlled flood experiment indicate that, during sediment-depleted conditions, sand deposited at higher elevation in downstream eddy sandbars is derived from the lower-elevation parts of upstream sandbars. Thus, controlled floods conducted under these conditions result in decreases in total eddy-sandbar area and volume (especially in Marble Canyon)*" (Topping et. al. 2006). It is not recommended to run future HFEs when these is no recent tributary sediment input and the channel sediment is depleted since it will erode sediment from long-term eddy storage (Hazel et. al. 2006a).

The 1997 high flow of 30,700 ft^3/s was conducted in November after Paria River flooding in August and September (Hazel et. al. 2000). The flow did not completely inundate the sand bars and the net bar thickness above 25,000 ft^3/sec did not increase. This was due to erosion of the existing high-elevation deposits offsetting any new deposition.

In 2000, another set of powerplant capacity flows (30,700 ft^3/s) were released during the low summer steady flows (LSSF) experiment. Unfortunately, there were little tributary sand inputs during 2000. Still the May and September 2000

HFEs did significantly increase volume and area of fine sediment in the eddy sandbars between the 8,000 ft^3/sec elevation and the 25,000 ft^3/sec elevation (Schmidt et. al. 2007). Changes above 25,000 ft^3/sec elevation were insignificant because these elevations were not deeply inundated. The volume below the 8,000 ft^3/sec water surface elevation decreased. Comparing the September 2000 HFE with the 1996 HFE shows that "*6 times less sediment was deposited as high-elevation eddy bars and channel-margin deposits, during the lower-discharge September 2000 Powerplant Capacity Flow, and a greater percentage of sediment was exported from Marble Canyon*." (Hazel et. al. 2006).

For the 2004 HFE, it was estimated that about 0.63 million metric tons of sand was supplied from the Paria River in the previous year (Topping et. al. 2010). The 2008 HFE had 1.12 million metric tons of sand. In 2004, the sandbars in Upper Marble Canyon were larger in total volume and area than after the 1996 flood. However, in Lower Marble Canyon, only 18% of the sandbars were larger in total volume and area above the 8,000 ft3/sec elevation than following the 1996 flood (Topping 2006). This was due to the fact that most of the new tributary sand in the system was located in Upper Marble Canyon when the HFE was conducted.

Based on monitoring surveys, the 2008 HFE deposited sand above the elevation reached by 25,000 ft^3/sec at nearly every study sight (Hazel et. al. 2010). Sandbars did not have a consistent response to the HFE, the total eddy thickness change are from -1.88 m to 1.13 m. Often, deposition above the 8,000 ft^3/sec elevation was offset by erosion below this elevation. The results showed that the total-site sand volume was greater for the 2008 HFE than for the 1996 and 2004 HFEs (Hazel et. al. 2010). In addition, there was less erosion at low elevations and in the main channel than from the 1996 and 2004 HFEs.

There was not a consistent response from every sandbar in Marble Canyon. The increases that are presented for total sand volume do not represent the site specific changes. There were four styles of sandbar change documented in the 2008 HFE response (Hazel et. al. 2010). The most common response was Style 1 (45%), which is characterized by a net increase in sand volume above and below the 8,000 ft^3/sec elevation. Style 2 (37%) is characterized by an increase in volume above the 8,000 ft^3/sec elevation, and degradation below this stage. Style 3 (16%) is characterized as net erosion at all stages and Style 4, which occurred at 1 site, is erosion above the 8,000 ft^3/sec stage and deposition below (Hazel et. al. 2010).

Using the comparison of the HFEs several lessons were discovered to be implemented of future HFEs. These are:

- A higher magnitude of flow will produce a larger sandbar response. Using a stage-discharge relationship developed for multiple locations within Marble Canyon (Hazel et. al. 2006b), the predicted stage increase is 3.5 feet between 31,500 ft^3/sec and 45,000 ft^3/sec. Therefore the sand can be deposited in higher available space for larger magnitude HFEs.

- The antecedent conditions are an important factor in the sandbar response. The three flows above 42,000 ft^3/sec resulted in increases in sandbar volume above the 8,000 ft^3/sec water surface elevation. Even though levels of sand enrichment were different for the three flows, the sandbar volume above 8,000 ft^3/sec was similar in Marble Canyon (Grams et. al. 2010). However, the 1996 flood *"resulted in a large net decrease in the total sand volume contained at the study site in Marble Canyon, while the 2004 and 2008 controlled floods resulted in smaller decreases in total sand volume"* (Grams et. al. 2010). Therefore, lesser enrichment results in greater erosion from the lower elevation portions of the eddies and degradation of the overall sand balance. This may not be a concern when HFEs are occurring many years apart and there is time to increase the sand balance with tributary inputs. However, if HFEs are happening once or twice per year, the overall sand balance and sand in the lower portions of the eddies becomes more of a concern.

These lessons were applied to the protocol that was set up for the EA. Based on the sandbar responses from previous HFEs, sand will be transported from lower eddy elevations to the higher elevations. The sandbars will begin to erode following an HFE. After the 2008 flood the median sandbar volume had returned to pre-HFE values in Marble Canyon 6 months after the HFE. The rate of erosion after each HFE differed and was "*positively correlated with the magnitude of average dam releases and inversely related to the magnitude of Paria River sand inputs for Marble Canyon*" (Grams et. al. 2010). The 2004 HFE has the lowest erosion rates while the 1996 HFE had the highest. These results provide motivation to conduct HFEs often to reverse the erosion that will inevitably occur. No experiments have been conducted where HFEs could potentially occur as often as every six months, monitoring and tracking the results and effects from repeated HFEs will be necessary.

Based on the literature summarized above, the HFEs recommended to occur by the modified sand budget model will cause an increase in the sand volume above the 8,000 ft^3/sec water surface elevation. Some sediment will be eroded from the lower eddies, but this amount will be minimized based on previous tributary sand inputs ensuring the system is not depleted. The redistributed sand will erode in the months following the HFE and the rate will be dependent on dam releases and any new tributary sand inputs.

A concept discussed in the existing literature is accommodation space, which is defined as the amount of space any one sandbar has to store sand. The success of frequent HFEs will depend on how much accommodation space is emptied from the previous HFE and available for sand storage in the next HFE. Depending on the rate of erosion there may be a diminishing rate of return on conducting multiple and consecutive HFEs. However, if the erosion rate is rapid, there may always be enough accommodation space in the sandbars to make an HFE efficient and successful at redistributing the sand to higher elevations. It is unknown how the system will react to frequent HFEs or multiple consecutive HFEs.

4 Conclusions

For the EA being produced by Bureau of Reclamation, the number of future HFEs (estimated frequency, magnitude, and duration) that could potentially occur was needed. A protocol was developed to determine when the conditions were feasible for an HFE to occur based upon past scientific monitoring and analysis. The protocol states that an HFE should be conducted when the increased flows will not cause a negative sand budget for the current accounting period. In addition, the HFE should be maximized for magnitude and duration to redistribute as much available sand as possible. A sand budget model developed by USGS (Wright 2010) was modified based on the protocol.

Future hydrology and sediment input traces were generated and used to run nine simulations in the modified sand budget model. Based on these, a HFE is performed in 56% of the potential implementation windows. Of these HFE's, 92% had a peak magnitude of 45,000 ft^3/sec. Typically HFEs occur in groups; 80% of the predicted HFEs had an HFE in the neighboring accounting periods. In the model, the occurrence of an HFE can be triggered by a certain level of sediment regardless of the hydrology. For the nine traces, the average monthly Paria sand load that always resulted in an HFE was 500,000 metric tons.

Based on the literature, the HFEs recommended by the modified sand budget model will cause an increase in the sand volume above the 8,000 ft^3/sec water surface elevation. Some sediment will be eroded from the lower eddies, but this amount will be minimized based on previous tributary sand inputs ensuring the system is not depleted. The redistributed sand will erode in the months following the HFE and the rate will be dependent on dam releases and any new tributary sand inputs.

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