APPENDIX E:

SEDIMENT RESOURCES TECHNICAL INFORMATION AND ANALYSIS

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E.1 INTRODUCTION

This technical appendix focuses on sediment resources. The sediment resource goal is to increase and retain fine sediment volume, area, and distribution in the Glen, Marble, and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes. One interpretation of this goal is to promote and maintain sandbars downstream of Glen Canyon Dam for the benefit of other resources. Currently, there is no peer-reviewed model or program that can simulate or predict sediment bar response to Glen Canyon Dam operations. Until such a model is available, other information and analyses were used in this draft environmental impact statement (DEIS) to analyze the effects alternatives would have on sediment resources. The sand budget model, which is peer reviewed and was used in the 2011 high-flow experiment (HFE) protocol environmental assessment (EA) (Reclamation 2011), provides the best available modeling method to estimate the effects of different flows on the potential for sandbar growth.

Seven alternatives were analyzed. Some of these alternatives would use condition-dependent or experimental elements that would be implemented under an adaptive management framework that would allow modification of flow and non-flow actions as new information is obtained. Critical uncertainties were identified that could lead to changes in flow and non-flow actions; these were used to identify multiple long-term strategies for those alternatives with condition-dependent actions (Alternatives B, C, D, and E). These long-term strategies were essentially different versions of the analyzed alternatives. The condition-dependent experimental elements included in the 19 strategies that were analyzed are presented in Appendix C; a full description of the alternatives can be found in Chapter 2 of this DEIS.

E.1.1 Analysis Period

Sediment analysis spanned water years 2014 through 2033 (i.e., October 1, 2013, to September 30, 2033) (Figure E-1). However, the hourly dam release data developed for the hydropower analysis (GTMax-Lite) followed a calendar year framework (i.e., January 1, 2013, through December 31, 2033). Development of sediment data for simulation input were analyzed in terms of sediment years (i.e., July 1, 2013, through June 30, 2033), which coincides with the accounting periods currently used by the Bureau of Reclamation (Reclamation) for determining whether or not a high-flow experiment (HFE) should be conducted (Russell and Huang 2010).

E.1.2 General Scope

In order to address uncertainty, the analysis conducted for this DEIS covered a range of hydrology scenarios and tributary sediment delivery scenarios. Hydrologic futures were developed using the Colorado River Simulation System (CRSS) (Appendix D). One-hundred and five 20-year hydrologic traces were developed from the 105-year period of record; for modeling (Section 4.1.1.1 of this DEIS), every fifth hydrologic trace was used, yielding 21 potential hydrologic futures to be analyzed.

Three sediment input time series were developed to address uncertainty in the future delivery of sand to the Colorado River from tributaries. Two main tributaries—the Paria River and the Little Colorado River—deliver sand to the Colorado River downstream of Glen Canyon Dam and upstream of Lake Mead. Three 20-year sediment traces were developed for the two tributaries (Section E.2.1.3), spanning the available historical data.

In summary, there were 19 long-term strategies, 21 hydrology traces per long-term strategy, and three sediment traces per hydrology trace. This produced 63 simulations per long-term strategy, 1,197 simulations in all.

E.2 METHODS

Resource models were used to evaluate and compare the impacts of alternatives. Figure E-2 illustrates the inputs, intermediate calculations, and output of the models. This appendix will describe and discuss those parts of the flowchart circled in red: the modified sand budget model (including development of model inputs) and the sediment metrics.

E.2.1 Sand Budget Model

E.2.1.1 Model Description

A reach-based sediment budget model for the Colorado River from Lees Ferry (river mile [RM] 0) to approximately Bright Angel Creek (RM 87) was developed by the U.S. Geological Survey (USGS) (Wright et al. 2010). Using gage data at RM 30, RM 61, and RM 87, the model was calibrated and validated to the time period of 2002–2009. The model uses empirically based rating curves, which are formulated on a particle-size-specific basis. On the basis of observed transport rates, the transport function changes when flows exceed 25,000 cfs. Initial sand bed size and thickness are user-specified for each reach (RM 0–RM 30, RM 30–RM 61, and RM 61–RM 87), and a budget is developed by tracking the incoming and outgoing suspended sand flux for each reach. The incoming sand flux for RM 0–RM 30 consists mainly of Paria River inputs, and ungaged tributaries in the reach are assumed to be 10% of Paria River inputs. The ungaged tributaries for RM 30–RM 61 are assumed to be negligible, so the flux into the reach equals the flux out of RM 0–RM 30. The flux into RM 61–RM 87 consists of the flux out of RM 30–RM 61, contributions from the Little Colorado River, and ungaged tributaries, which are assumed to be negligible. Figure E-3 provides a schematic of the sand budget model.

E.2.1.2 Sand Budget Model Modifications

The sand budget model has been updated to meet the specific analytical needs since its inception. During analysis for the 2011 High Flow Experiment (HFE) Environmental Assessment (EA) (Reclamation 2011), a protocol was developed to determine whether a HFE could be implemented to improve/maintain the sandbar sediment resource (Russell and Huang 2010). The model was updated to include the HFE protocol and to identify the largest HFE that could be implemented within each sediment accounting period without causing the Marble Canyon sediment balance to be negative for that period. Marble Canyon is the focus of the sediment balance because (1) the sand budget model was calibrated and validated for the first 87 mi downstream of Lees Ferry; and (2) the gage record for the Little Colorado River is relatively short, and therefore there is less confidence in using the data for predictive purposes. The protocol in the model assumes that the implementation of an HFE occurs on April 1 for the spring accounting period and on November 1 for the fall accounting period.

For the LTEMP DEIS, the water volumes used by each HFE were accommodated by adjusting monthly volumes in the rest of the water year instead of simply adjusting the releases for the remainder of the implementation month as was done for the HFE EA. One of two different reallocation schemes is implemented depending on the alternative: a sequential reallocation scheme or an average reallocation scheme.

The sequential reallocation scheme was applied to Alternatives A and B (because they have the same monthly release volume allocations). The months from which to reallocate water were specified in order, along with the minimum release volume for each month and the minimum release flow rate. Water was reallocated from the months, in order, until the water volume needed for an HFE was achieved. If the volume needed for an HFE could be borrowed from the first month in the list, then no water was borrowed from the following listed months. If the necessary HFE volume could not be taken from the first month without violating either the minimum monthly volume or the minimum release discharge, then the next month in the list was accessed for additional volume.

The average reallocation scheme was applied to the rest of the alternatives because their monthly release volume distributions differed from Alternative A. This method borrowed a percentage of the monthly volume from each month specified. The volume of water borrowed was not the same across months, but the percentage borrowed from each month was consistent; a higher monthly volume before reallocation means more water taken and applied to the HFE volume. There is a user-specified minimum release discharge that cannot be violated for the average reallocation scheme.

Another modification made to the sand budget model (which did not affect the triggering of an HFE) was to track the necessary parameters to determine whether a trout management flow (TMF) would be triggered for a water year. For a description of TMFs, see Chapter 2 of this DEIS. A simple binary file was developed to identify water years meeting the requirement for a TMF; parameters indicating trout recruitment and the triggering of a TMF are all flow related.

The primary results from the first iteration of the modified sand budget model are two files per simulation: one identifying the timing and size of HFEs, and one identifying timing of TMFs. This information is fed back to the GTMax-Lite model (Figure E-2) for refined hourly dam release hydrographs.

E.2.1.3 Modified Sand Budget Model Inputs

Primary model inputs to the sand budget model are (1) flow hydrographs and (2) tributary sand inputs. The initial conditions of sand bed thickness and average bed grain size were also specified; these values are constant across simulation and are not alternative dependent.

Flow Hydrographs

The model-predicted suspended sand transport rates were calibrated and validated (as part of the model development; Wright et al. 2010) at gage measurement locations, namely the gages at RM 30, RM 61, and RM 87. The flow hydrograph at these locations needs to be specified for the sand budget model and are developed using the Colorado River Flow, Stage, and Sediment (CRFSS) model. The CRFSS model has a one-dimensional unsteady-flow model component that routes a dam-release flow hydrograph and provides hydrographs at locations requested by the user. The CRFSS model uses average channel geometry based on previously measured cross-sections in Marble and Grand Canyons (Wiele and Smith 1996; Wiele et al. 2007). For each dam release hydrograph provided by GTMax-Lite (Figure E-2), there were three hydrographs developed by the CRFSS model (at RM 30, RM 61, RM 87) for use in the modified sand budget model.

Tributary Sand

Both the Paria River and the Little Colorado River have sediment records that were used to develop a time series of sand load (a sediment trace). Although the Little Colorado River record is for only 18.5 years, it is the best available data set. Three sediment traces were developed for each tributary to address uncertainty in future tributary sand delivery. Sediment data were obtained from two sources: published data from the Grand Canyon Monitoring and Research Center (GCMRC 2015) and from D. Topping (Topping 2014). The period of record for the two tributaries and the sources of the data are presented in Table E-1.

The model simulation period covers 21 calendar years, which corresponds to 41 sediment accounting periods, or ~20.5 sediment years (Figure E-2). An index sequential approach was used to develop statistics for each record. In general, an index sequential method cycles through each year in a historic record and generates time series (or traces) for a specific duration; for years toward the end of the record, the requisite time period is achieved by “wrapping around” to the beginning of the record. This technique is typically used for hydrologic data cycling through water years (Reclamation 2007; Ouarda et al. 1997), whereas the method is employed here for sediment data and cycles through sediment years. The “wrap around” for the sediment analysis means that for the Paria River, the fall 2013 accounting period is followed by the spring 1964 accounting period; likewise, for the Little Colorado River the fall 2013 accounting period is followed by the spring 1994 accounting period. The record for the Little Colorado River is short enough relative to the 21-year period that every index sequential sediment trace covers the entire period of record.

Paria River. Because fall 2013 is the first full accounting period for which an HFE would be considered in the simulation, only index sequential segments beginning with fall accounting periods are used in the statistical analysis. The three traces selected were approximately the 10%, 50%, and 90% non-exceedance traces from the index sequential statistics. The three selected traces for the Paria River also cover the entire period of record. Figure E-4 presents the sand input from the Paria River for the historical record grouped into accounting periods, along with the index sequential 41-accounting period (20.5-year) sand loads. Only the 20.5-year sand load sequences beginning with a fall accounting period are presented in Figure E-4; these are the data from which the statistics are developed for identifying three representative traces. Figure E-5 presents the cumulative sand load for the three traces that were identified for the use in the DEIS modeling. Again, these traces were identified based on cumulative sand load and to ensure the entire historical record is represented in the modeling.

These three traces are not consistently low, medium, and high relative to each other throughout the 20-year period. Moving from beginning to end of the simulation period, s1 (sediment trace 1) is not always less than s2, and s2 is not always less than s3. In fact, s3 is comparable to s2, except in the last couple of years when the s3 trace jumps significantly; this jump corresponds to the fall 1980 accounting period. In addition, s1 has the most sediment contributions for approximately the first 3 years. These are three different sediment traces that were selected to be representative of the historical record.

Once the three sets of 41 accounting periods were identified for use in the simulation, the necessary simulation records (traces) were completed by applying the appropriate sections of the historical record. The periods of record used for s1, s2, and s3 are presented in Table E-2.

Little Colorado River. The record for the Little Colorado River is shorter than the simulation period, so every trace covers the entire period of record. In addition, the HFE protocol as implemented in the modified sand budget model assesses the balance of sand in Marble Canyon to determine whether an HFE is simulated. The balance of sand in Eastern Grand Canyon—and therefore the sediment input from the Little Colorado River—is less critical to the simulations and analysis performed for this DEIS.

The index sequential method for the Little Colorado River was performed on a calendar year basis, and the simulation periods for s1, s2, and s3 are presented in Table E-3. Figure E-6 presents the sediment traces used as input for the modified sand budget model.

Initial Conditions

The initial conditions to be specified in the sand budget model for each reach are bed thickness and median bed sediment grain size, D_{50}. The initial conditions specified for the DEIS analysis come from the best available data nearest the simulation start date of January 1, 2013. Wright et al. (2010) found that varying initial bed D_{50} by ±10% from the initial estimated values (0.4, 0.3, and 0.3 mm for UMC, LMC, and EGC, respectively) yielded between 3 and 7% difference in total flux for the three reaches; varying initial bed thickness from the initial estimated values (0.4, 0.5, and 0.5 m for UMC, LMC, and EGC, respectively) by ±10% yielded a difference in total sand flux of less than 0.5%. The simulations conducted for this analysis used initial condition values for UMC, LMC, and EGC of 0.46, 0.38, and 0.43 mm, respectively, for grain size and 0.30, 0.37, and 0.27 m, respectively, for bed thickness.

High Flow Events

The modified sand budget model identified the largest HFE that would not violate water and sediment availability rules. The HFEs that the model considered are user specified. Eighteen HFEs that are specified for this analysis (Table E-4), and HFEs 1–13 are consistent with the HFEs considered for the HFE EA (Reclamation 2011). Longer-duration HFEs (A–E in Table E-4) were suggested for consideration in the DEIS, and two alternatives consider HFEs lasting longer than 96 hours: Alternative D and Alternative G. HFE C in Table E-4 was originally defined as lasting 240 hours at 45,000 cfs for Alternative G. Alternative D was crafted after seeing the results of the Alternatives A, B, C, E, F, and G (Section 2.2.4 of this DEIS), and HFE C in Table E-4 was defined as 250 hours for this alternative.

Proactive spring HFEs would be triggered based on hydrology. Conceptually, a large snowpack in the mountains leads to a prediction of a wet year, and if the predicted annual runoff volume is great enough (greater than 10 million ac-ft, or 10 maf) then a proactive spring HFE would be implemented. The purpose of this HFE is to redistribute the available bed sediment onto sandbars and channel margins so that it would be stored at elevations above those of the subsequent large runoff volume. The proactive spring HFE implemented in the model is identical to HFE 6 in Table E-4 in terms of peak discharge and duration at peak discharge.

E.2.2 Sediment Metrics

Prior to modeling for the LTEMP DEIS, a number of metrics were crafted to evaluate the alternatives in terms of their performance with regard to the sediment resource goal. The metrics developed prior to modeling were surrogates intended to be representative of sediment resource response; it was assumed that if the surrogate performed well, the sediment resource also would respond well. The metrics developed were the sand load index (SLI), the standard deviation of high flows (SDHF), and the sand mass balance index (SMBI).

E.2.2.1 Sand Load Index (SLI)

The potential for building sandbars was estimated using the SLI, which is a comparison of the mass of sand transported at RM 30 when river flows ≥31,500 cfs relative to the total mass of sand transported at all flows, as shown in equation 1:

$$SLI = \frac{Q_{s,Q>31.5}}{Q_{s,total}} \quad (1)$$

where:

SLI = sand load index

$Q_{s,Q>31.5}$ = sand flux at RM 30 when river flows at RM 30 are greater than 31,500 cfs

$Q_{s,total}$ = total sand flux at RM 30 during analysis period.

The index varies from 0 (no sand transported at flows ≥31,500 cfs) to 1 (all sand transported at flows ≥31,500 cfs). An SLI of 0 would indicate that there are no flows above 31,500 cfs during a simulation; the alternative that there are flows above 31,500 cfs but no sediment flux occurring is for all practical purposes impossible.

The larger the SLI for an alternative, the more potential there is for bar growth. The SLI only estimates the potential for (and not actual) bar growth, because all sandbars have a maximum potential deposition volume; the closer any given bar is to full, the less deposition will occur (Wiele and Torizzo 2005).

E.2.2.2 Standard Deviation of High Flows (SDHF)

This index was intended to represent a greater likelihood of more robust sandbars. Historical sandbar surveys indicate that individual bars respond differently to different HFEs (Hazel et al. 2010). Some sandbars are smaller after a 45,000 cfs event. Equation 2 shows how this value is calculated for each water year, and the metric is averaged across the 20-water-year analysis period.

$$SDHF = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \quad (2)$$

where:

SDHF = standard deviation of high flows

N = sample size (in this case, 63 per alternative)

x_i= individual observed peak discharge, cfs

$\bar{x}$ = sample mean of peak discharges, cfs.

E.2.2.3 Sand Mass Balance Index (SMBI)

This index quantifies the amount of sand that is left in storage in Marble Canyon (RM 0 to RM 61) at the end of a simulation relative to the amount of sand that is present at the beginning of the simulation. This is the most direct application of the modified sand budget model; it tracks the amount of sand that comes into the individual reaches compared to the amount of sand that leaves the individual reaches (Figure E-7). This index is not directly representative of the resource goal. However, this metric does provide insight into how the amount of sediment in Marble Canyon is affected by dam operations. If more sand comes into Marble Canyon than leaves Marble Canyon, there will be an increase in stored sand, and a positive SMBI. Conversely, a greater amount of sand leaving Marble Canyon than entering will yield a negative SMBI.

E.3 RESULTS

Two iterations of the modified sand budget model were completed for each simulation (Figure E-2). The first iteration determined the timing and size of triggered HFEs, as well as identifying whether TMFs would be triggered. This information was passed back to GTMax-Lite where the hourly dam release hydrographs were refined based on the HFE schedule and TMF schedule.

The second iteration of the modified sand budget model did not allow additional HFEs to be implemented because the refined GTMax-Lite dam releases already include the HFEs and TMFs. The second iteration was used to obtain sediment-related data for sediment metrics to be calculated for each alternative.

E.3.1 HFEs Determined by Alternative

The sediment metrics for each alternative are closely related to the number of HFEs that occur for the alternative. The number of HFEs is not a sediment metric itself, but understanding the HFEs that occur under an alternative helps to clarify the sediment metrics discussed in the following sections. The average number of HFEs that occur (across 63 simulations per alternative) is compared, along with the number of HFEs that occur based on sediment trace (average across 21 simulations). Results for long-term strategies C3, E3, E5, and E6 are not presented in this section, because HFEs are not included in these long-term strategies.

Figure E-8 presents the breakdown of the average number of HFEs for each long-term strategy (across 21 hydrology and 3 sediment traces) by HFE type (Table E-4). Only Alternatives D and G allow for HFEs longer than 96 hours, and Alternative G has the most HFEs on average. Alternatives A and B have the fewest HFEs on average. Under Alternative A (no-action alternative) the HFE protocol would expire in 2020, so a little more than half of the simulation period does not have HFEs simulated. Alternative B stipulates that HFEs would not be implemented more often than once every 2 years. This limits the number of HFEs to one-fourth of the simulation period. Alternative F has a 24-hour 45,000-cfs flow at the beginning of the spring peak period (e.g., on May 1) as part of the alternative definition. Those events are not captured in Figure E-8; this figure represents the sediment-triggered and hydrology-triggered HFEs identified from the modified sand budget model. More information on the alternative definitions can be found in Chapter 2 of this DEIS.

Figure E-9 compares the average number of HFEs simulated (not by HFE type) for the three different sediment traces. Remember that s1, s2, and s3 do not equate to low, medium, and high; they are three sediment traces intended to be representative of the historical sediment records in terms of exceedance probability, as well as ensuring that the entire period of record is represented by the three traces. Figure E-9 shows some variability among the sediment traces, although the general trends between alternatives as shown in Figure E-8 are maintained. Sediment trace s2 commonly has the lowest number of simulated HFEs. Sediment trace s1 has the most simulated HFEs for Alternatives A, B, and F. Sediment trace s3 has the most simulated HFEs for Alternatives C (except long-term strategy C4), D, and G. Sediment traces s1 and s3 are very similar for Alternatives E (except long-term strategy E4) and F with regard to the number of HFEs triggered.

The majority of HFEs are triggered in the fall, because sediment from the Paria is related to monsoonal precipitation and the majority of the sediment delivery occurs in the fall. Fall HFEs account for 77% of all HFEs simulated; the remaining 23% of HFEs that occur in the spring include proactive spring HFEs, which are triggered by hydrology (wet years) and not by sediment delivery.

E.3.2 Metrics

Plots have been developed for each metric to statistically describe the alternative performance from the 63 different simulations for each long-term strategy. The statistics represented in these plots include a weighting scheme based on each sediment trace's exceedance probability. The weighting scheme for the box and whisker plots is as follows: s1 = 0.1754, s2 = 0.6313, s3 = 0.1933. In addition, a different set of weights was used for a climate change analysis to represent the fact that future hydrology in the Upper Colorado River Basin is expected to be drier than the historical hydrology (Section 4.16.1.2 of this DEIS). Plots using climate change weighting are provided for each sediment resource metric in Section E.3.3.

The box and whisker plots provide information on the following statistical representations of the distribution of performance across 63 simulations per long-term strategy: minimum, maximum, mean, median, 25th percentile, and 75th percentile, as described in Figure E-10.

E.3.2.1 Sand Load Index (SLI)

The SLI as described in Section E.0 reflects the potential for sandbar growth. Figure E-11 presents SLI values for all long-term strategies. Overall, Alternative G has the highest SLI values, followed by Alternatives F, D, C and E. Alternatives A and B have the lowest SLI values, which is consistent with the number of HFEs that can be triggered under each alternative.

Figure E-11 matches the general pattern of the number of HFEs shown in Figure E-8. One notable exception is Alternative F; Figure E-8 represents the sediment-triggered and hydrology-triggered HFEs, whereas Figure E-11 includes data from the alternative-defined spring events that occur each year under Alternative F regardless of sediment availability.

There is a nonzero SLI for long-term strategies C3, E3, E5, and E6, even though there are no HFEs simulated for these long-term strategies. Some hydrologic years are wet enough to necessitate flows above 31,500 cfs being released from Glen Canyon Dam as normal (non-HFE) operations. The sand transported while flows are above 31,500 cfs under these conditions contributes to a nonzero SLI.

E.3.2.2 Standard Deviation of High Flows (SDHF)

As described in Section E.2.2.2, this metric was intended to reflect variability in flow, which was thought to be positively related to the ability to build more robust sandbars. Figure E-12 presents the statistical distribution of SDHF values for the long-term strategies, which is similar to the general pattern shown for the SLI in Figure E-11.

The SDHF mean is plotted against the SLI mean in Figure E-13. A strong correlation exists between the SDHF and the SLI. Therefore, the SDHF was not considered with the SLI for alternative comparison in this DEIS.

E.3.3 Sand Mass Balance Index (SMBI)

This metric does not represent the sediment metric directly (Section E.2.2.3); however, it does provide an index to relative changes in sediment balance that would result under different alternatives. If an alternative reduces the overall sediment balance (the amount of sediment in the sandbars and eddies, and on the channel bed) then this net depletion will result in less sediment being available for bar building during future HFEs.

The only long-term strategies that do not significantly reduce the sediment balance over the duration of the simulation period are those that do not have HFEs (long-term strategies C3, E3, E5, and E6), as shown in Figure E-14. The mass balance of sediment is affected by high flows. HFEs have been called a “double-edged sword” by Rubin et al. (2002) because they necessarily export relatively large volumes of sand in order to transfer sand to high-elevation portions of sandbars (Wright et al. 2008). There is an inverse relationship between sandbar building potential and sediment balance; more sandbar building potential reduces the sediment remaining within the channel. Figure E-15 plots the mean SMBI relative to the mean SLI. Although there is variation among the alternatives, a higher SLI tends to create a larger net deficit of sand (lower SMBI value) in Marble Canyon. Two exceptions are Alternatives B and D. Alternative B would produce a large net deficit in SMBI but has a relatively low SLI; the relatively low SLI is a result of the limited number of HFEs under this alternative, but this does not produce a correspondingly low SMBI because the larger daily fluctuations during intervening flows transport more sediment. Alternative D has relatively high SMBI and SLI values; more HFEs (including longer duration HFEs) yields the higher SLI value and the combination of relatively even monthly distributions along with relatively small daily fluctuations contributes to a higher SMBI.

E.3.4 Alternative Performance under Climate Change Scenarios

Weights were applied to hydrology traces to reflect expected changes in hydrology under climate change. This weighting scheme was intended to represent future hydrology in the basin, which is expected to be drier than the historical hydrology (Section 4.16.1.2 of this DEIS). Figure E-16 presents SLI values calculated under the long-term strategies using the climate change weights. Figure E-17 shows that there is little difference in long-term strategy performance in terms of SLI when comparing the climate change weights to the historical weights. The small difference that does exist could be described as a slight improvement in performance under the climate change weighting.

Figure E-18 presents SDHF values under long-term strategies when the climate change weights were used. Figure E-19 shows that there was little difference between SDHF values calculated using the climate change weights and those calculated using the historical weights. The most notable difference is a slight reduction in the 75th percentile, which indicates less variability in the metric when climate change weights are used.

Figure E-20 presents SMBI values under long-term strategies when the climate change weights were used. Figure E-21 shows that there was some difference between SMBI values calculated using the climate change weights and those calculated using the historical weights. When climate change weights were used, the interquartile ranges and the means were higher, which indicates less net depletion. Interestingly, the minima and maxima do not change appreciably, meaning these extremes are likely due to specific simulations (combination of hydrology and sediment traces).

E.3.5 Relative Impacts of Dam Operations and Hydrology on Performance

Modeling results were evaluated to determine the effect of the following management actions on sediment resources: proactive spring HFEs, spring HFEs, fall HFEs, TMFs, daily fluctuations and intervening flows, load-following curtailment, low summer flows, and general hydrology (wet vs. dry). These evaluations were made using the model runs of the various long-term strategies, which included some, but not necessarily all, elements. Additional modeling did not take place to answer these questions.

HFEs, whether they are proactive spring HFEs, spring HFEs, or fall HFEs, are the most influential management action in terms of sediment resources. Whether a given HFE type (magnitude and duration) occurs in the fall or the spring does not affect the sediment resource differently. The timing of sediment delivery from the Paria River (during the summer-fall monsoon season) leads to larger and more frequent fall HFEs, but that is due to input, not management actions.

TMFs did not show a significant impact on the sediment resource. This is due in part to the fact that one of the primary factors in triggering a TMF is a spring HFE, which, in the model, increased trout recruitment (Section 4.4.1.2 of this DEIS). Spring HFEs have a relatively large effect on the SLI and SMBI that tends to mask a TMF's impacts on sediment. Another reason TMFs have little impact on sediment because of their effect on release volume. In order to provide the flow for TMFs, the average flow in the remainder of the late spring/early summer period tends to be lower than if there were no TMF. The effect of higher flows for the TMFs and the lower flows means a very minor difference in net sediment transport.

Figure E-22 shows the time series of flow (Q) at RM 30, the SLI, and the SMBI for the simulation hydrology trace 1/sediment trace 3 (t01s3) for the period March 1, 2021, to August 1, 2021. Long-term strategies C1 and C2 are plotted for comparison; both simulations have the same HFE triggered in spring 2021, but TMFs are implemented under C1 but not C2. In the figure, the TMF flows can be seen in early May, June, and July in the top graph. Notice the time series of SLI and SMBI show a strong signal response in early April due to the HFE, and practically no signal response from the TMF flows.

Alternatives C and E differ in daily fluctuation levels, as well as monthly volume allocations; this is the best comparison we can make (without performing targeted modeling) on the effects of daily fluctuations. Alternative C has lower daily fluctuations than Alternative E, but has relatively high spring volume compared to the more even monthly pattern of Alternative E. Although lower daily fluctuations reduce sediment transport, higher monthly volumes increase transport. It was not possible to reconcile the relative importance of daily fluctuations and monthly volume allocations without additional modeling. However, a comparison of Alternative C and Alternative E using the long-term strategy where no HFEs are allowed (long-term strategies C3 and E3) was made. This comparison takes into account both daily fluctuations and monthly volume allocations. There was no difference in SMBI values between long-term strategies C3 and E3 (Figure E-23), and there was a minor difference in SLI values (Figure E-24). Because there are no HFEs in long-term strategies C3 and E3, all of the values for SLI are below 0.2 and any differences between these alternatives are minor.

Load-following curtailment is a management action intended to retain sediment for HFEs by reducing daily fluctuations before and/or after the HFE for a period of weeks or months. Load-following curtailment is specified as fluctuations being limited to ±1,000 cfs about the mean daily flow (a 2,000 cfs range of fluctuation). This management action does not appear to make a difference in the modeled metric values, because an HFE will necessarily reduce the non-HFE mean flow around which daily fluctuations occur; the daily fluctuations associated with lower means tend to have fluctuation ranges not much greater than the ±1,000 cfs specified for load-following curtailment. Figure E-25 shows the smaller fluctuation range leading up to a fall

HFE and the associated impact on SLI and SMBI (hydrology trace 6, sediment trace 3). Long-term strategies E1 and E2 are compared here, but the same comparison could be made using other long-term strategies (C1 and C2 or D1 and D2) with similar trends. Although there are differences in metric values between E1 and E2 for the months following the HFE, the SMBI is different by only 9 ktons at the end of the water year, and the SLI is the same by the end of the water year.

Low summer flows are a management action intended to provide warmer water for humpback chub during the summer. These lower flows would also be expected to conserve sediment inputs during the monsoon period. Implementing low summer flows in the summer requires increasing average monthly release volumes in other non-summer months (especially in the spring), thereby counteracting, in the long term, any short-term increase in sediment conservation (Figure E-26).

Annual inflow volume that reflects annual variation in precipitation and runoff is the main driving force on sediment processes. Release volumes are governed by legal release requirements (Section 1.9 of this DEIS). For the SLI, wetter hydrology means a lower metric value (Figure E-27). This is true for the long-term strategies that do not have limitations on the number of HFEs that can be triggered. The trend lines with a positive slope in Figure E-22 are Alternative A (no HFEs after 2020), Alternative B (long-term strategies B1 and B2; not more than one HFE every 2 years), and long-term strategies C3, E3, E5, and E6 (no HFEs). Based on modeled SMBI values, wetter hydrology is expected to transport more sediment downstream under all long-term strategies (Figure E-28).

E.4 LAKE DELTAS

The impact of sediment delta formation due to different alternatives must be inferred, because there are no models for this physical process. The following discussion and conclusions are based on existing data and on some of the modeling data for the sediment resource alternative analysis.

Lake deltas are formations that occur when sediments transported in high-energy riverine flow fall out of the water column as the river enters a lake and loses energy. The Colorado River, along with a number of smaller rivers (that used to be tributaries to the Colorado River but are now emptying directly into Lake Powell or Lake Mead) have deltas that form in locations determined by reservoir elevation. As the elevations of the lakes change, the locations of the deltas will also change (Figure E-29).

Lake Powell and Lake Mead deltas can be grouped into two categories: those deltas whose size and location would be affected by dam operations, and those whose location, but not size, would be affected by dam operations.

Only the Colorado River delta in Lake Mead can be affected in terms of both location and size; all other deltas' positions are affected by reservoir elevation (and their delta size is unaffected by dam operations). Using historical data from the GCMRC data portal (http://www.gcmrc.gov/discharge_qw_sediment/stations/GCDAMP), less than half (approximately 46%) of the suspended sand load reaching the gage above Diamond Creek (USGS gage 09404200) since October 2002 can be accounted for as suspended sand leaving Marble Canyon (USGS gage 09383100). The other half of the suspended sand reaching Diamond Creek comes from tributaries downstream of Marble Canyon, most notably the Little Colorado River. Figure E-30 compares the cumulative sand load above Diamond Creek (RM 225) to the cumulative sand load at Desert View (RM 61). This figure demonstrates that the amount of sediment passing RM 225 is approximately 22,000 ktons in the approximately 12.5-year time span since October 2002; this can be extrapolated to about 35,200 ktons of sand for a 20-year period (the same duration as the LTEMP analysis period). Similarly, the approximately 10,000 ktons of sand that have passed RM 61 since October 2002 can be extrapolated to approximately 16,200 ktons of sand for a 20-year period.

The mean SMBI resulting from the 20-year simulations indicates that there may be anywhere from 1,000 to 3,300 ktons of net loss in Marble Canyon sand, depending on the alternative. This decrease in Marble Canyon sand increases the amount of sand going past RM 61 by approximately 6% for Alternative A and 20% for Alternative F, as compared to historical data. Assuming all of the sand leaving Marble Canyon eventually passes Diamond Creek, these increased fluxes leaving Marble Canyon represent less than a 10% change in sand flux at RM 225 compared to the historical data.

The alternatives considered will have minimal impacts on the size of the Colorado River delta in Lake Mead, which is the only delta that could be affected in terms of size and location by Glen Canyon dam operations.

The positions of deltas in Lake Powell and Lake Mead are directly affected by reservoir elevation (Figure E-29). Changes to reservoir elevations are calculated in the CRSS model (Section 4.1 and Appendix D of this DEIS). The elevation of the lakes is compared to full pool elevations of 3,700 ft for Lake Powell and 1,229 ft for Lake Mead. The lake elevations from the alternatives are compared on a monthly basis and minima, means, and maxima were determined for the 63 simulations under each alternative. Figure E-31 presents the pool elevation for Lake Powell and Figure E-32 presents the pool elevation for Lake Mead. There is more variability related to differences in hydrology (compare the minimum and maximum for a given month) than there is related to different alternatives (compare colors across months). Pool elevations are ultimately controlled by regional hydrologic conditions and will not be affected by the alternatives. Alternative F is slightly different than the other alternatives because the monthly release volumes are low through winter. This small difference is not as pronounced as the variability due to annual inflow.

E.5 LIMITATIONS AND KNOWN ISSUES

E.5.1 Geographic Scope

The geographic scope of this DEIS includes the Colorado River from Glen Canyon Dam downstream, and west, to Lake Mead (Section 1.5.1 of this DEIS). This geographic scope in terms of Colorado River Mile is from RM 15 (Glen Canyon Dam; RM 0 is at Lees Ferry) to RM 347 (Hoover Dam). The numerical model upon which the sediment resource analysis is based extends from RM 0 to RM 87, although uncertainty in sand load from the Little Colorado River limited the analysis to Marble Canyon (RM 0 to RM 61).

E.5.2 Modeling Improvements

The average reallocation scheme (Section E.2.1.2) requires specification of a minimum flow rate about which fluctuations occur. The modeling for alternatives that use the average reallocation scheme and that allowed for daily fluctuations (Alternatives C, D, and E) have a fluctuation range specified at 5,000 cfs to 8,000 cfs. Due to differing up- and down-ramp rates, the average discharge is not 6,500 cfs but is closer to 6,521 cfs. Alternatives C and E used a specified flow rate of 6,500 cfs, but this error was found before modeling of Alternative D, and 6521 cfs was used for this alternative. Fixing the minimum flow rate for Alternatives C and E may result in a small adjustment to the results, but should not change relative rankings among alternatives.

Load-following curtailment was not implemented for all long-term strategies of Alternatives C and E. Fixing this issue is not expected to affect modeling results.

In a few cases during the modified sand budget modeling, sufficient water volume was identified to sustain an HFE; however, the water surface elevation in Lake Powell was below the minimum power pool intake elevation. This did not allow GTMax-Lite to develop refined hourly flows. In such cases, the sand budget model for the appropriate simulation(s) was run again without allowing an HFE to occur during the problem accounting period. A potential fix for this issue could result in the occurrence of a small HFE. This fix is expected to affect results for a given simulation; however, when considering the averaging across 63 simulations, the net effect is expected to be small.

Initial conditions for bed thickness and bed material size may not have been consistent between the first and second runs of the modified sand budget model for all long-term strategies. Wright et al. (2010) found that varying initial conditions by ±10% made less than a 7% difference in model results, so this fix is not expected to make a difference in alternative analysis.

One of the long-term strategies for Alternative D (D2) included sustained low flows for benthic invertebrate production (Section 2.2.4 of this DEIS). The set of months from which water is reallocated to support an HFE is not the same set of months when these sustained low flows are implemented, and implementing this in the model proved iterative and perhaps not as representative as it could be. Further modification to the sand budget model may improve the implementation of this flow management action; anticipated effects of this effort are unknown.

E.6 REFERENCES

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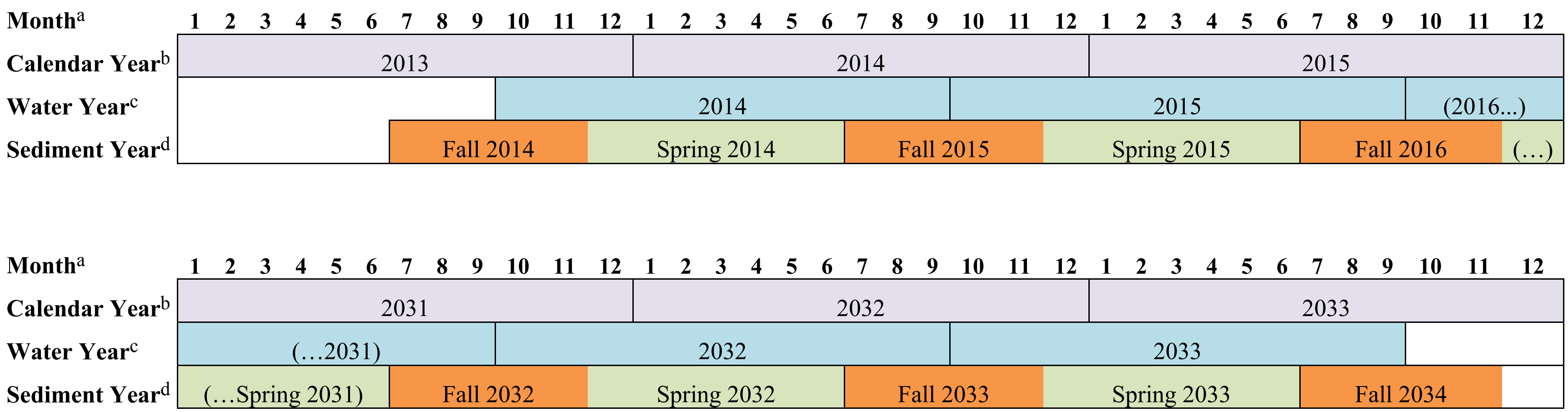

[a] 1 = January; 2 = February; 3 = March; 4 = April; 5 = May; 6 = June; 7 = July; 8 = August; 9 = September; 10 = October; 11 = November; 12 = December.

[b] Model simulations run for 21 calendar years.

[c] Analysis of alternatives covers 20 water years.

[d] Two accounting periods (spring/fall) per sediment year.

FIGURE E-1 Comparison of Calendar, Water, and Sediment Years

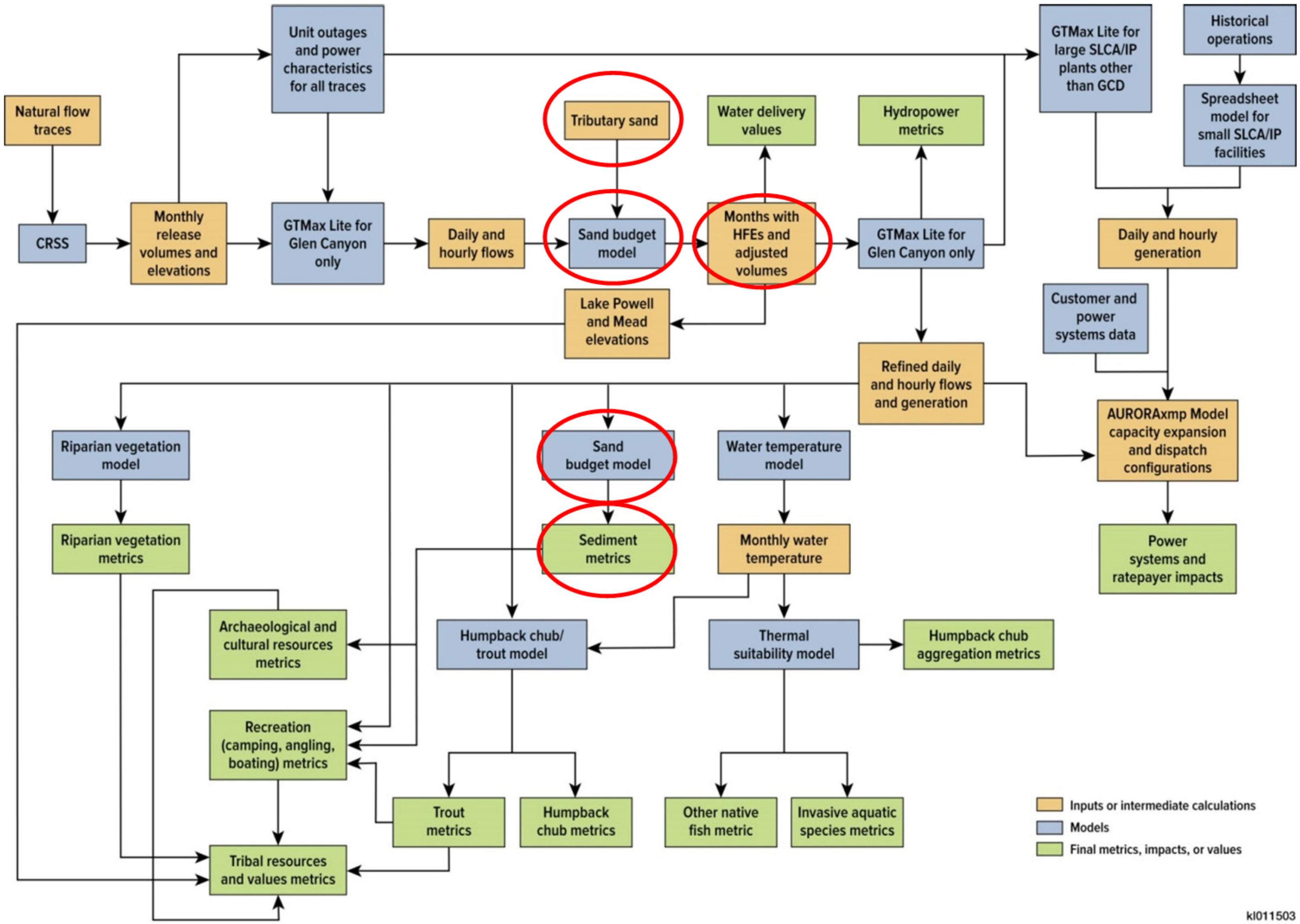

FIGURE E-2 Model Flow Diagram for Analyses Showing Inputs, Intermediate Calculations, and Output

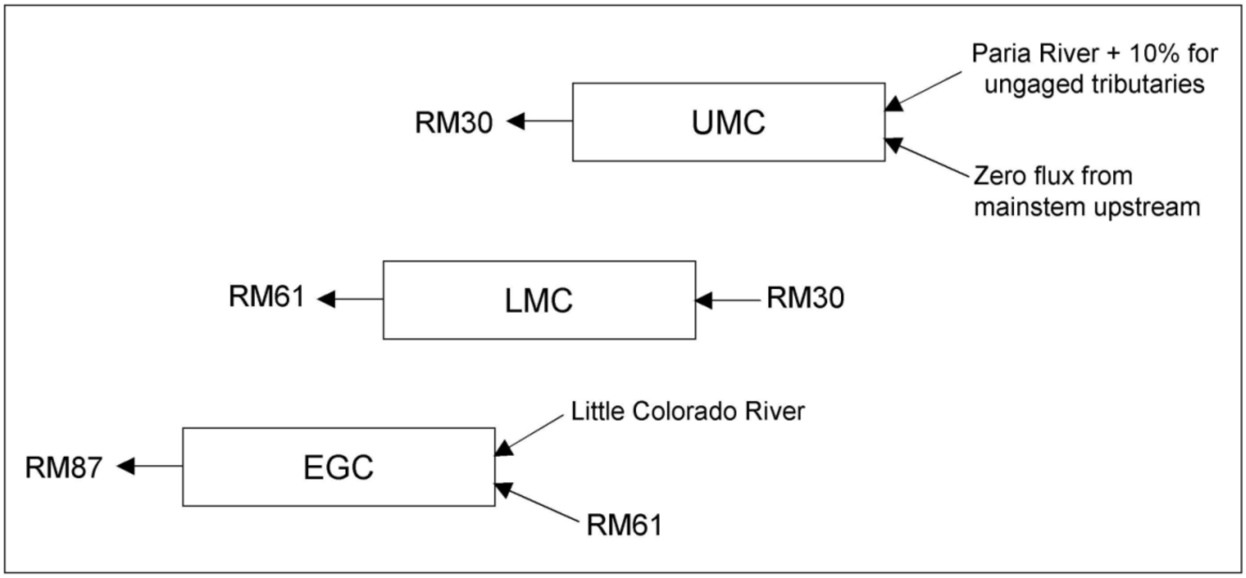

FIGURE E-3 Conceptual Schematic of the Sand Budget Model (UMC = Upper Marble Canyon; LMC = Lower Marble Canyon; EGC = Eastern Grand Canyon)

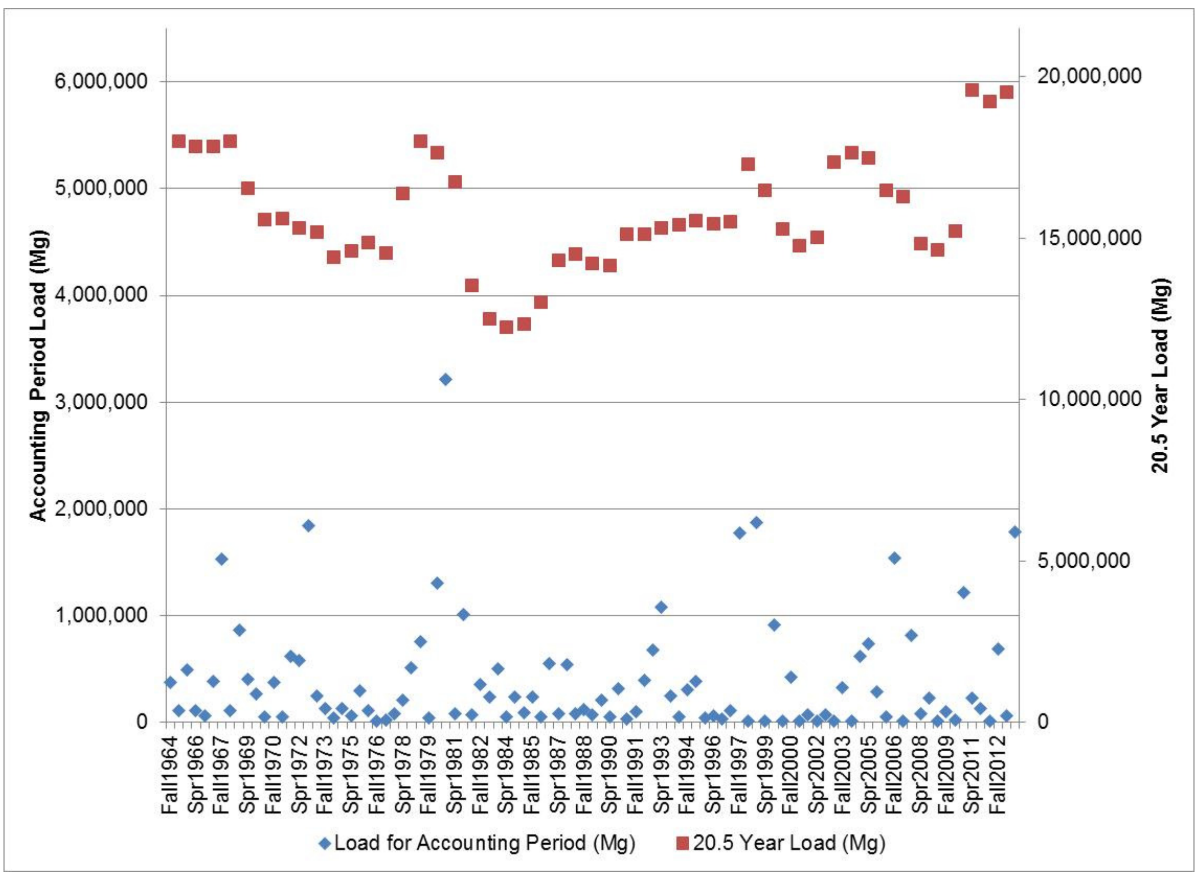

FIGURE E-4 Historical Paria Sediment Load per Accounting Period and the 20.5-year Load for the Trace That Begins in Each Fall Accounting Period

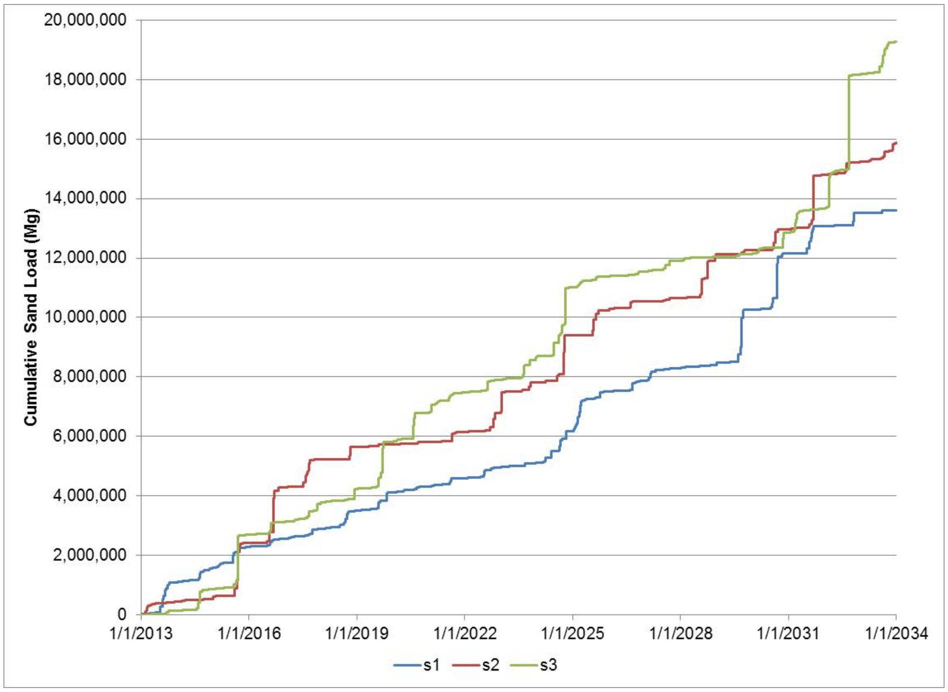

FIGURE E-5 Sediment Traces s1, s2, and s3 for the Paria River (presented as cumulative load) Used in the Modeling to Account for Uncertainty in Future Delivery

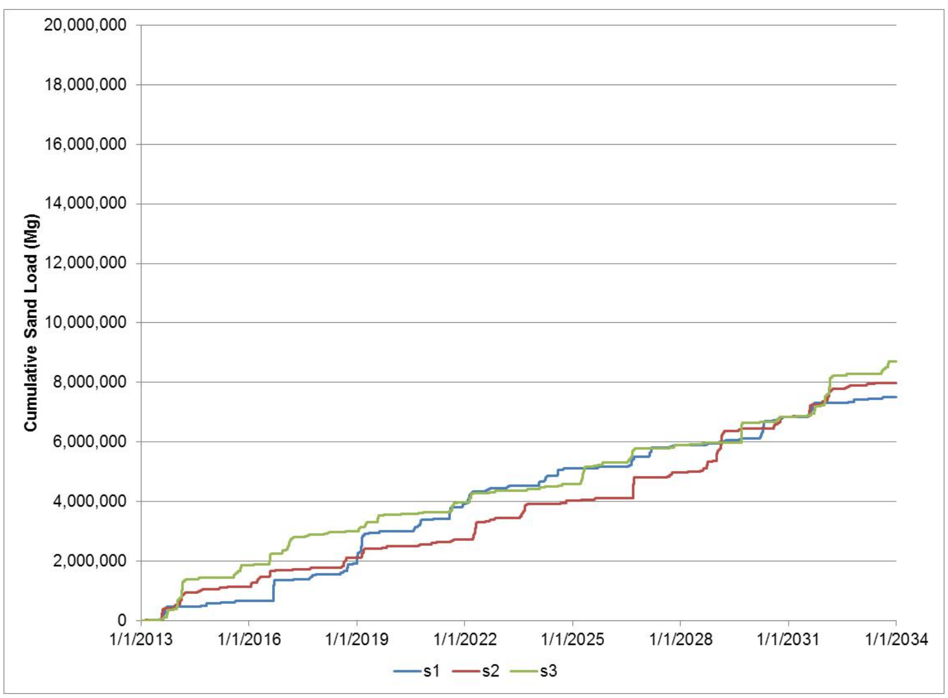

FIGURE E-6 Little Colorado River Sediment Traces (presented as cumulative loads) for s1, s2, and s3 Used in the Modeling to Account for Uncertainty in Future Delivery

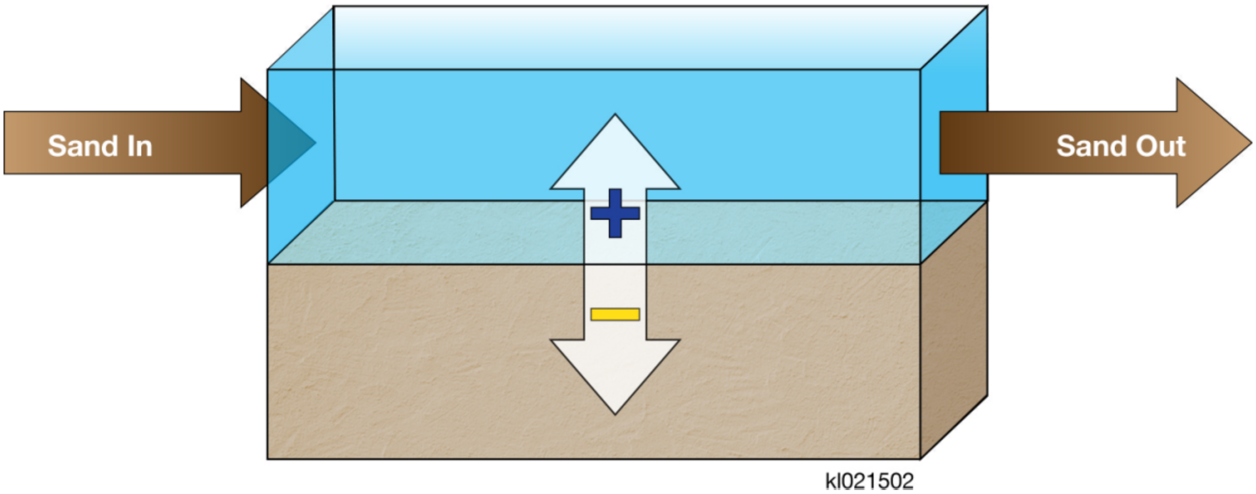

FIGURE E-7 Conceptual Representation of the Sand Mass Balance Index

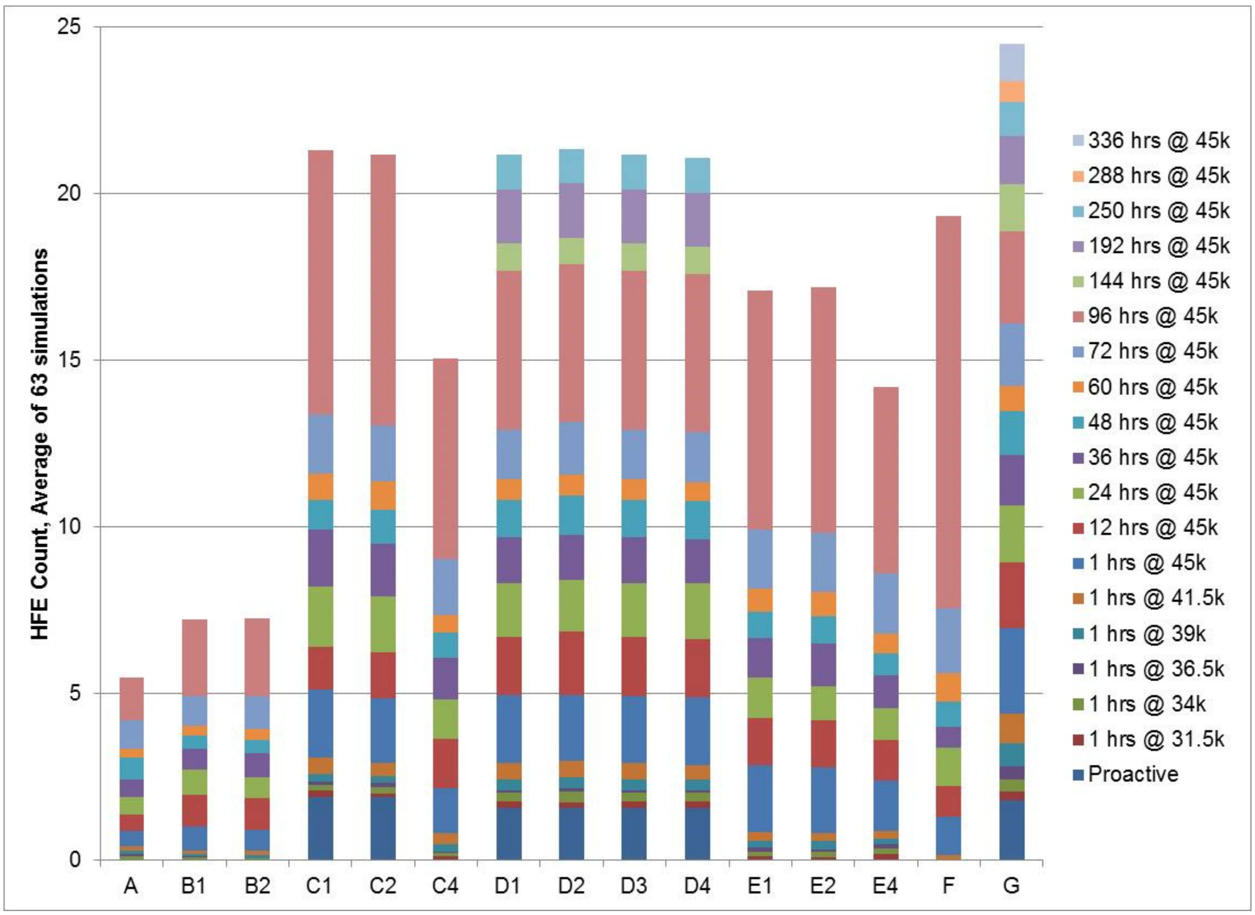

FIGURE E-8 Average Sediment and Hydrology Triggered HFE Count by Type for Each Long-Term Strategy (long-term strategies C3, E3, E5, and E6 by definition have no HFEs)

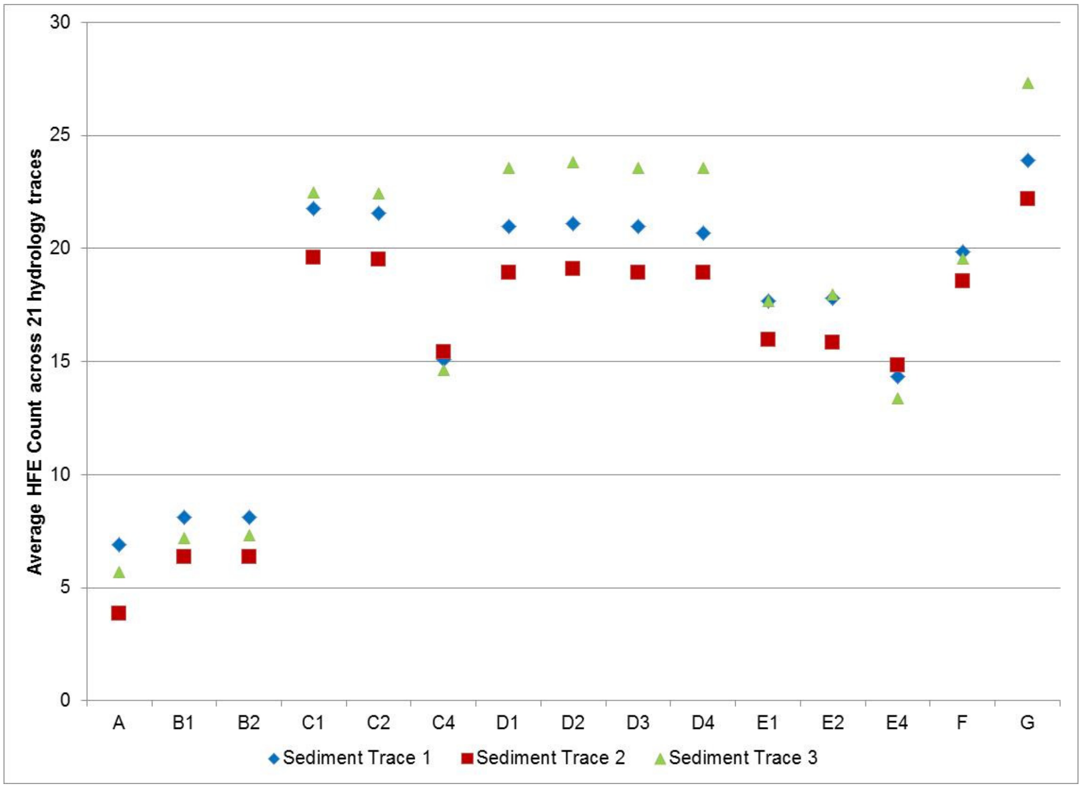

FIGURE E-9 Average HFE Count for Sediment Traces s1, s2, s3 for Each Long-Term Strategy (long-term strategies C3, E3, E5, and E6 by definition have no HFE)

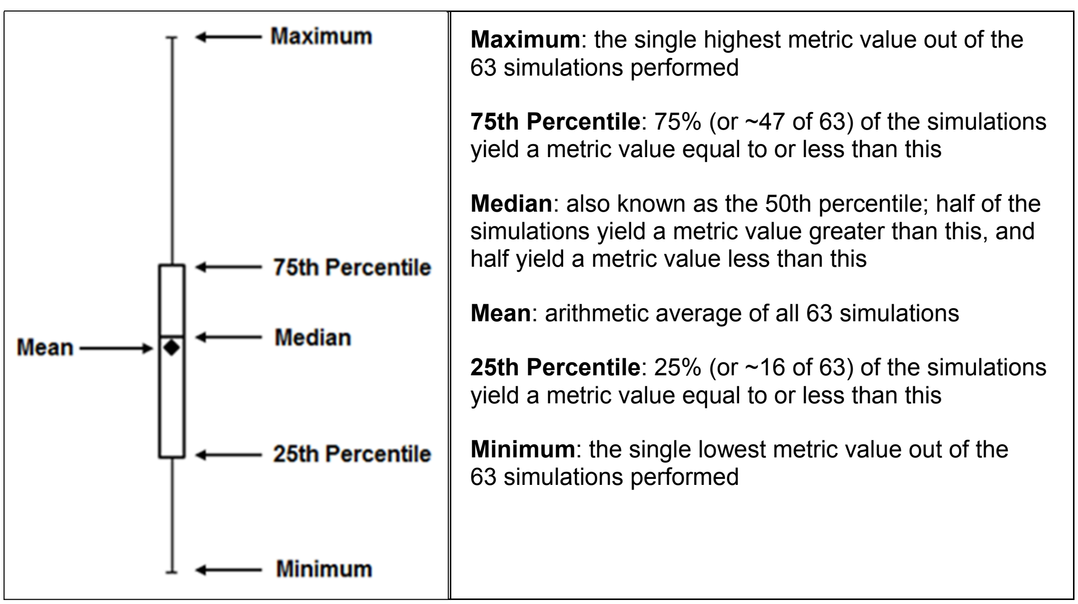

FIGURE E-10 Definition of the Statistics Represented by the Box and Whisker Plots Used in This Analysis

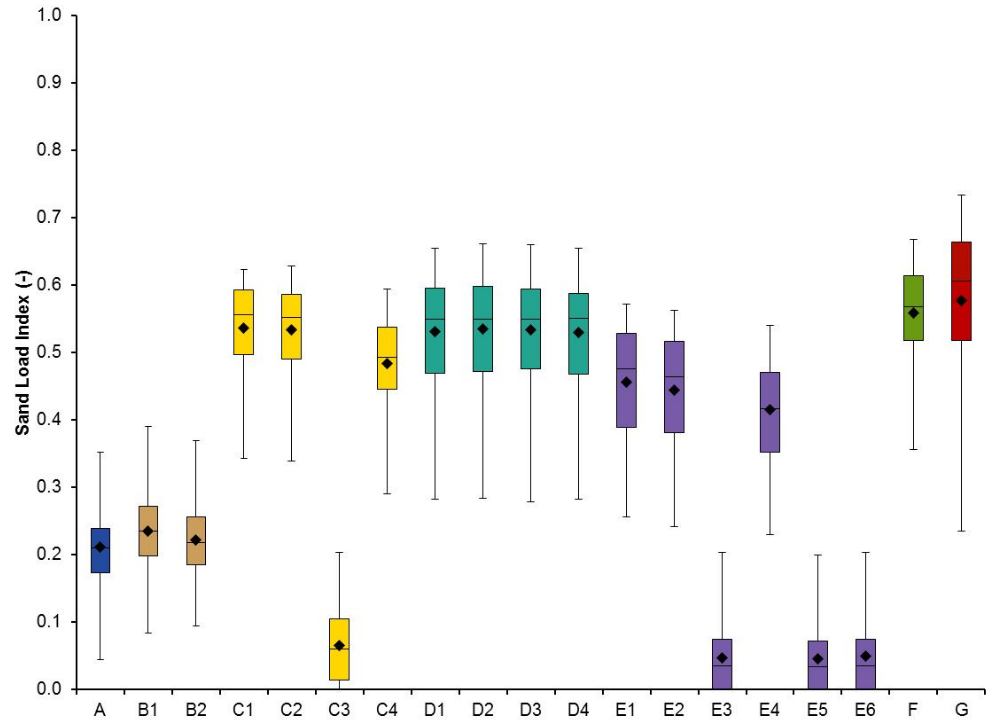

FIGURE E-11 Sand Load Index Statistics from 63 Simulations for Each Long-Term Strategy

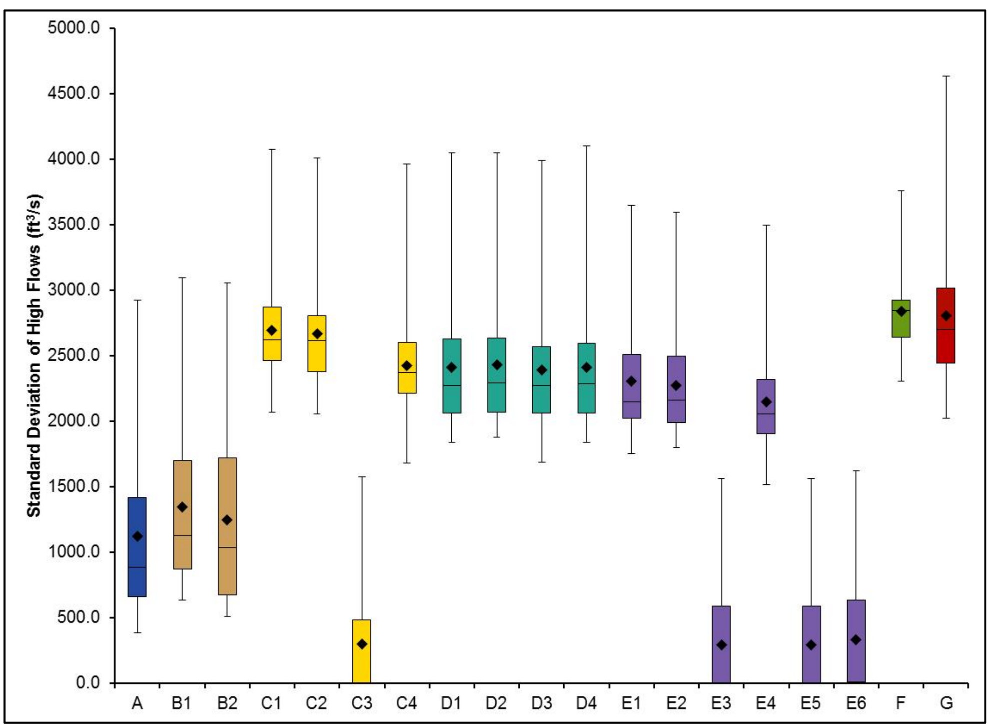

FIGURE E-12 Standard Deviation of High Flows Statistics from 63 Simulations for Each Long-Term Strategy

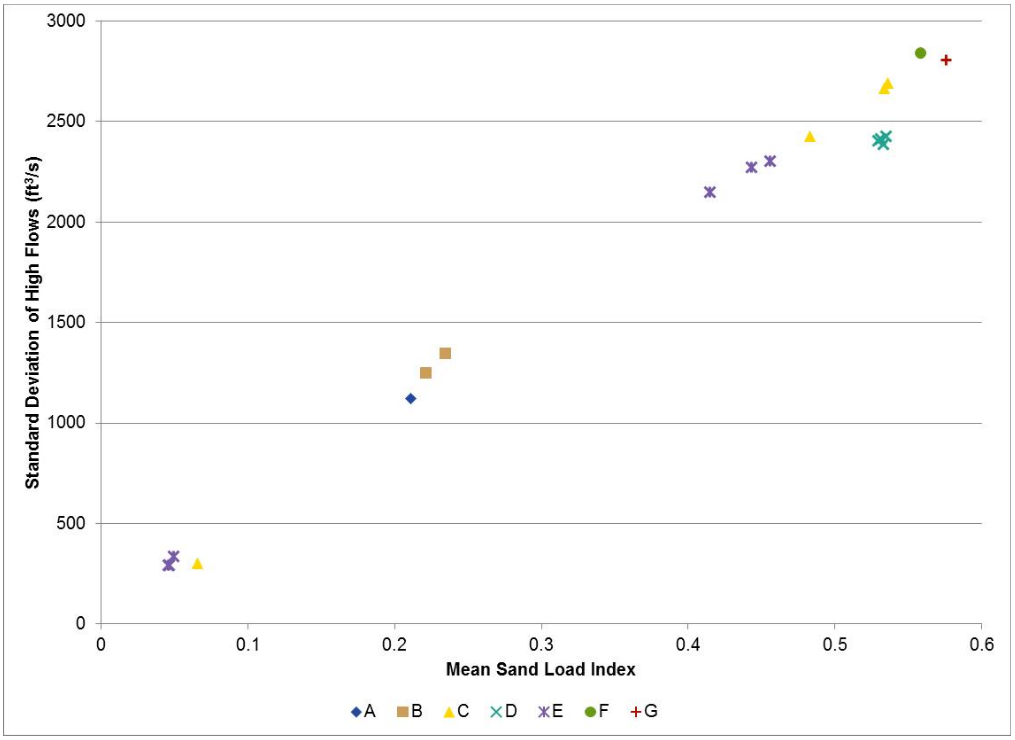

FIGURE E-13 Correlation between SDHF and SLI (r = 0.99, *P* < 0.001)

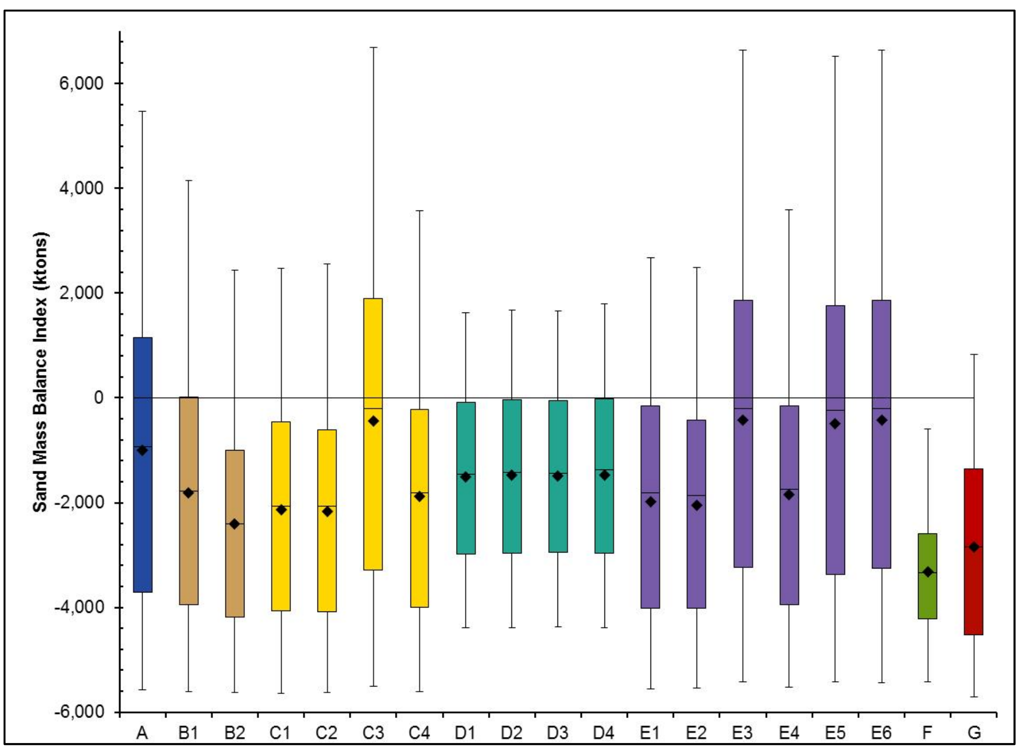

FIGURE E-14 Sand Mass Balance Index Statistics from 63 Simulations for Each Long-Term Strategy

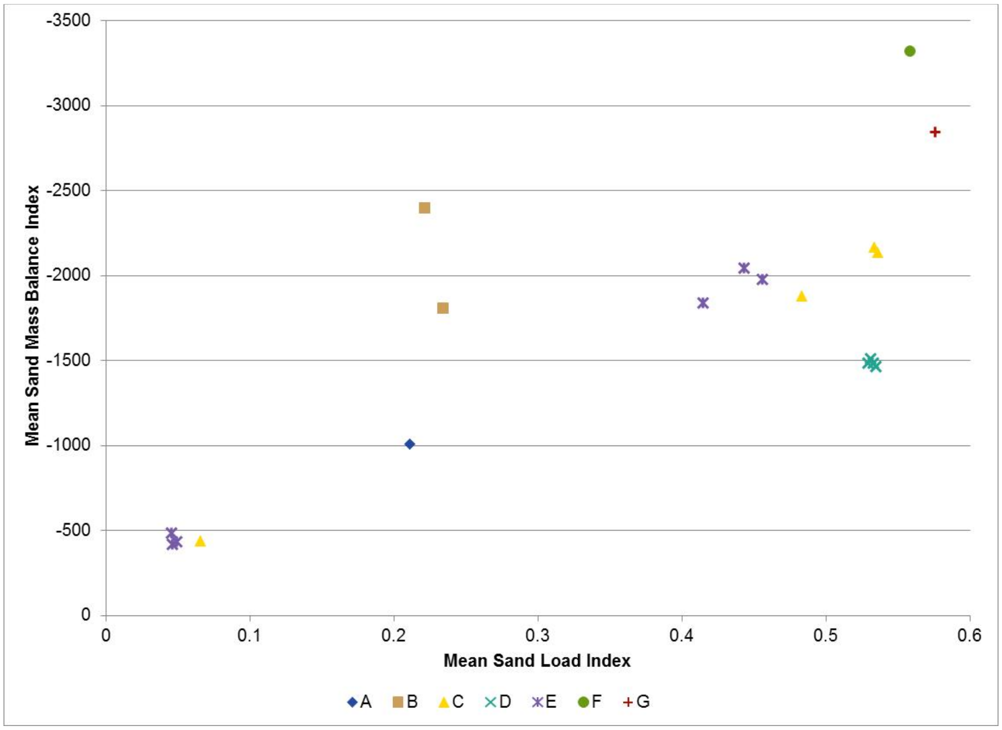

FIGURE E-15 Correlation between SMBI and SLI (r = 0.75, *P* < 0.001) (Note that the *y*-axis values are negative and in reverse order.)

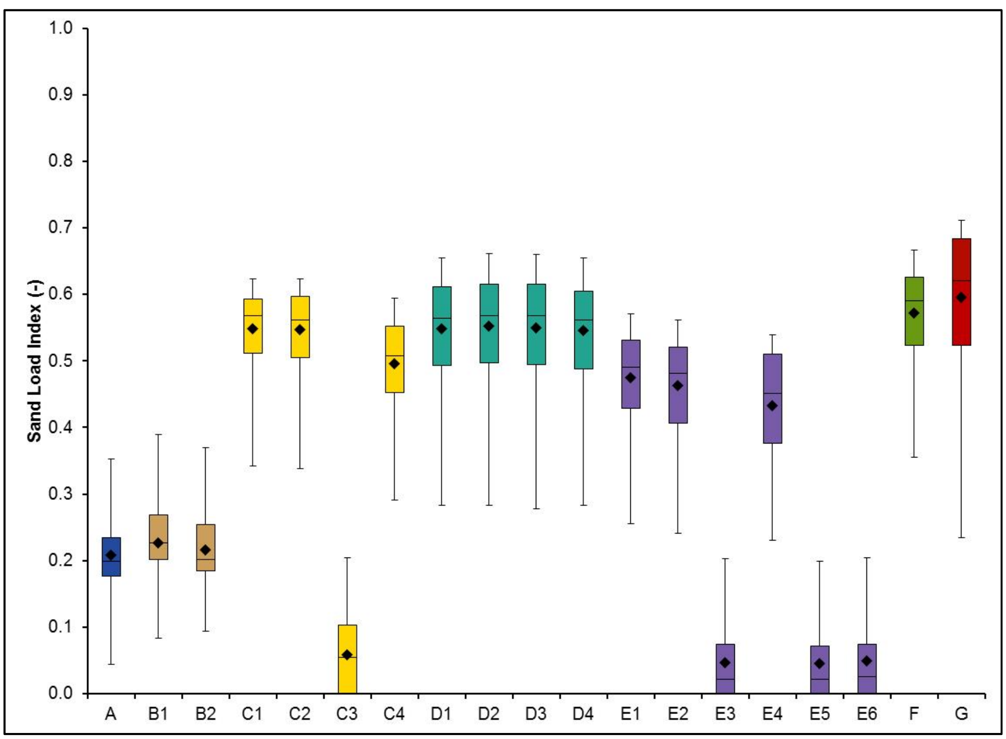

FIGURE E-16 Sand Load Index for Long-Term Strategies Using Climate Change Weights (Compare to Figure E-11, which uses historical weights.)

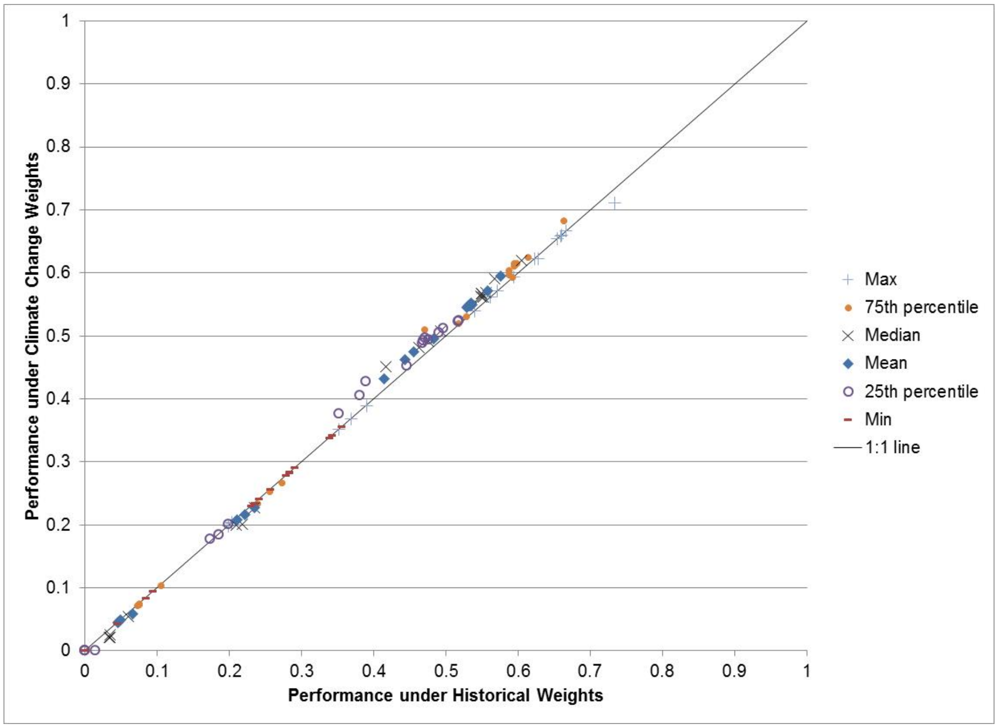

FIGURE E-17 Comparison of the Sand Load Index between Climate Change and Historical Weights

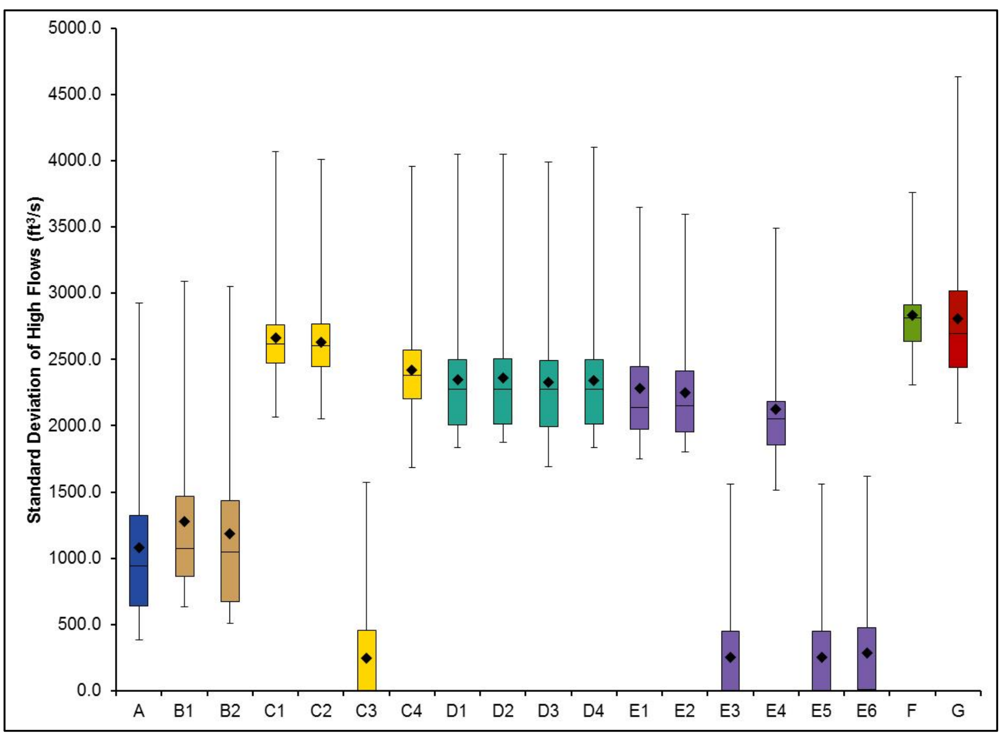

FIGURE E-18 Standard Deviation of High Flows Using Climate Change Weights (Compare to Figure E-12, which uses historical weights.)

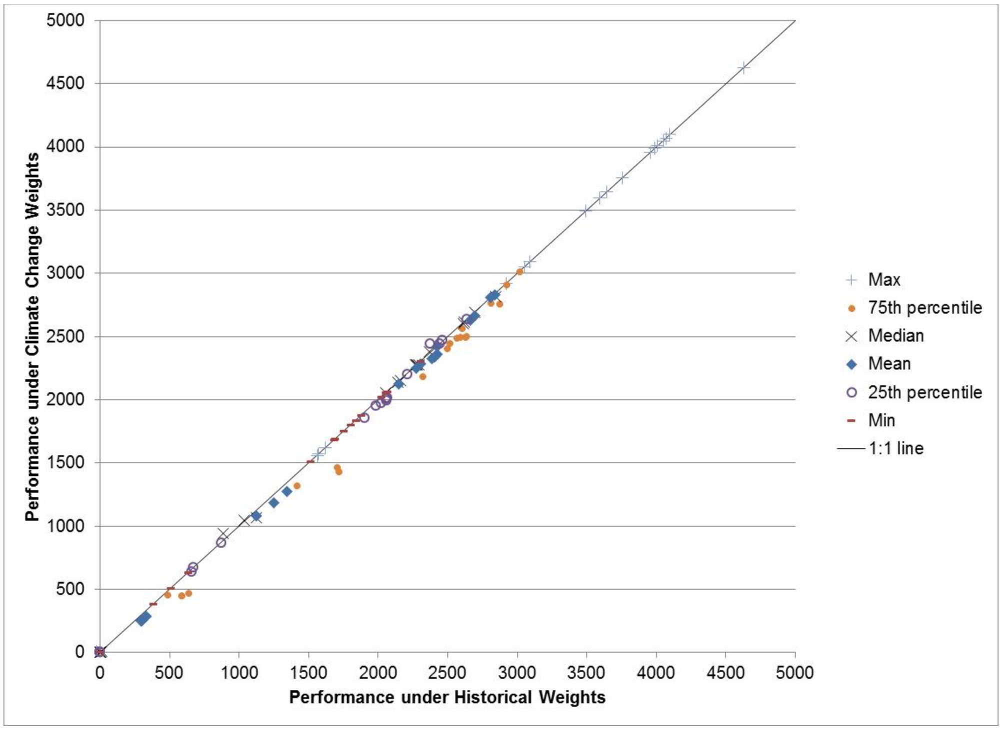

FIGURE E-19 Comparison of the Standard Deviation of High Flows between Climate Change and Historical Weights

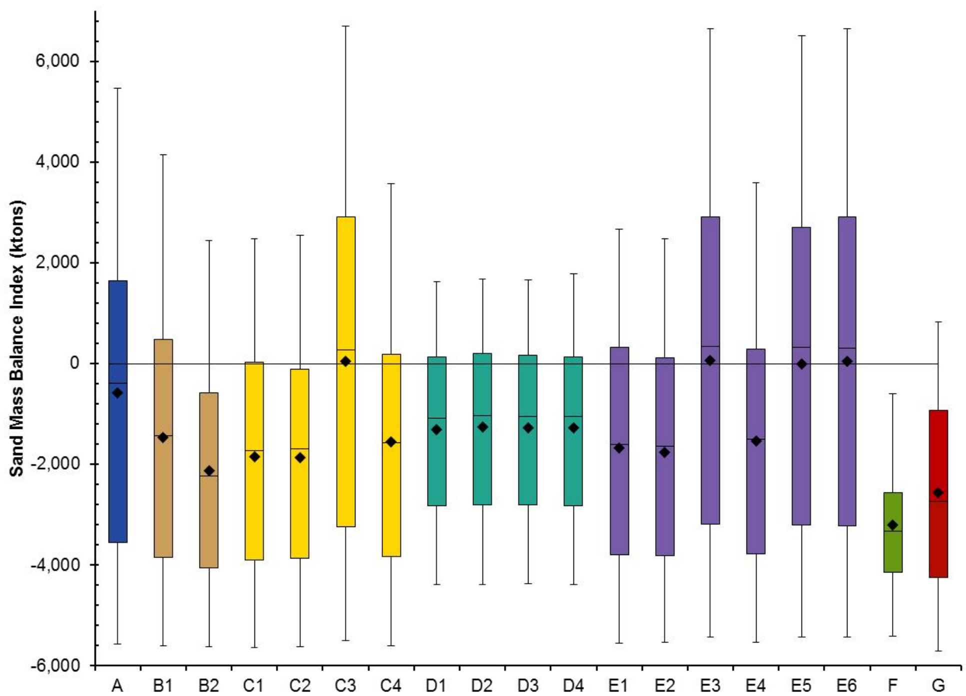

FIGURE E-20 Sand Mass Balance Index Using Climate Change Weights (Compare to Figure E-14, which uses historical weights.)

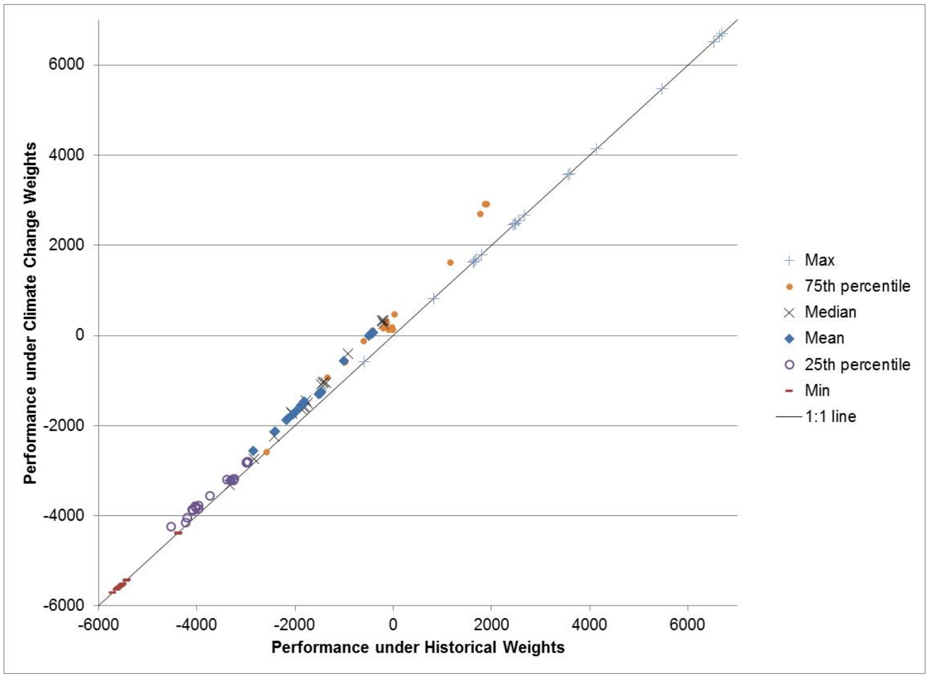

FIGURE E-21 Comparison of the Sand Mass Balance Index between Climate Change and Historical Weights

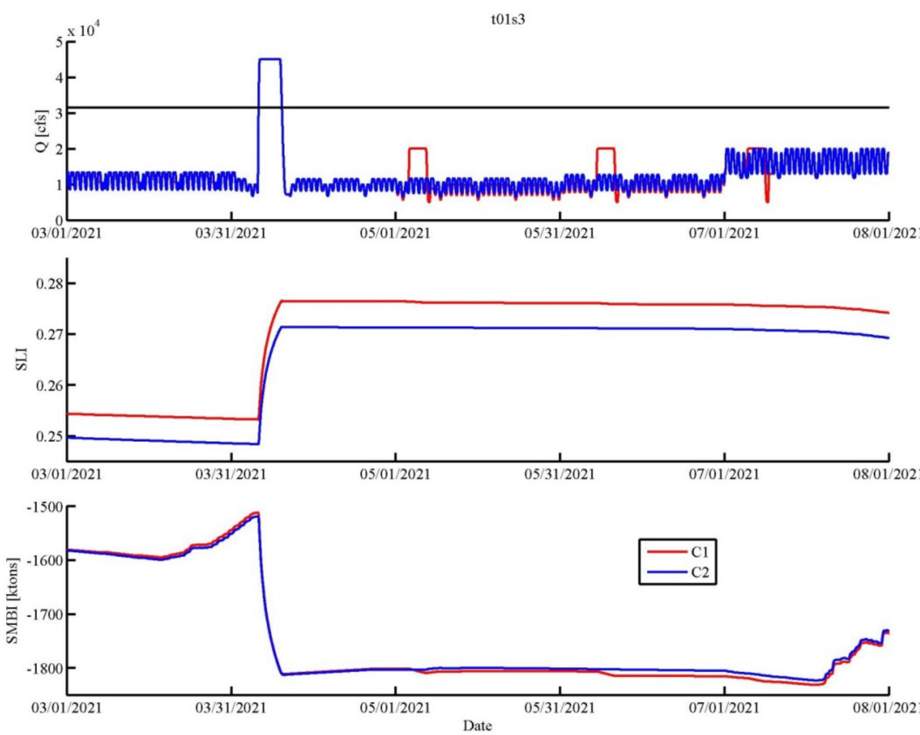

FIGURE E-22 Comparison of Long-Term Strategies C1 and C2 for Hydrology Trace 1, Sediment Trace 3 (TMF flows have very little effect on SLI or SMBI.)

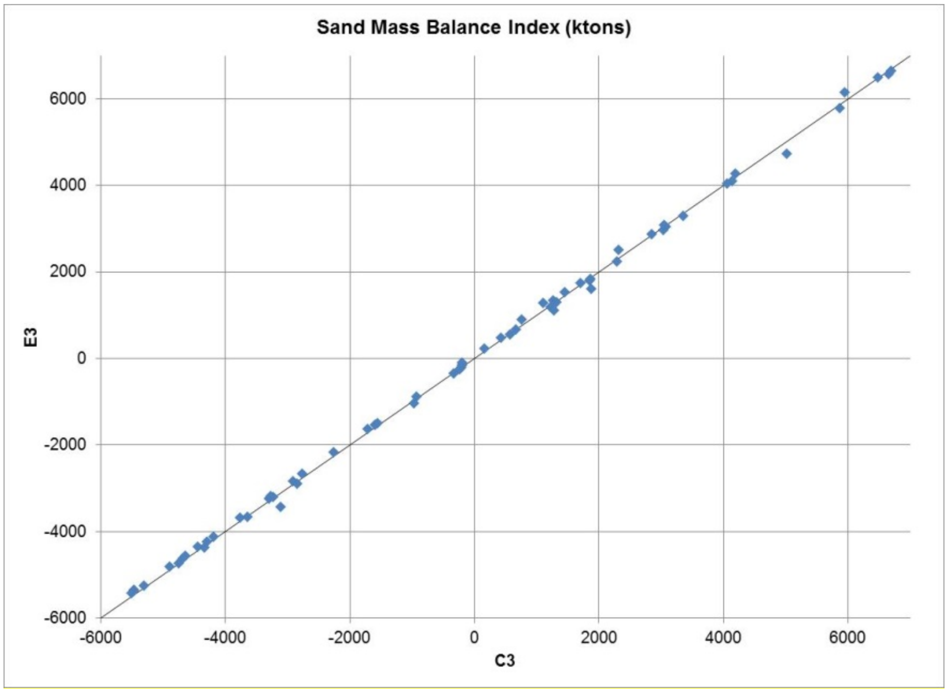

FIGURE E-23 SMBI for Alternative E Plotted against Alternative C (The combination of intervening flows and monthly volumes yields no difference in SMBI.)

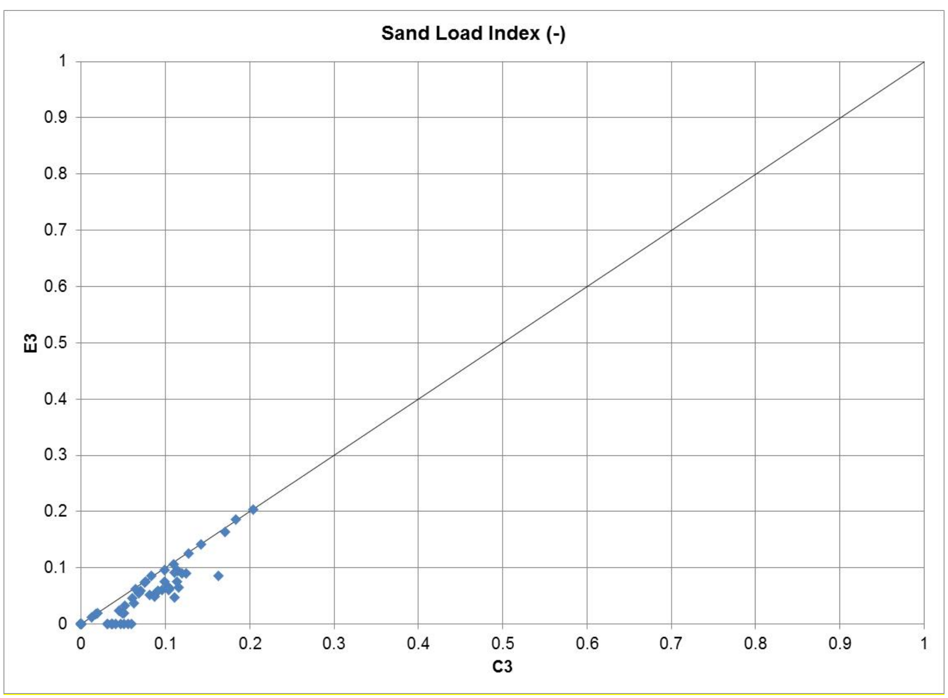

FIGURE E-24 SLI for Alternative E Plotted against Alternative C (The combination of intervening flows and monthly volumes yields small differences in SLI.)

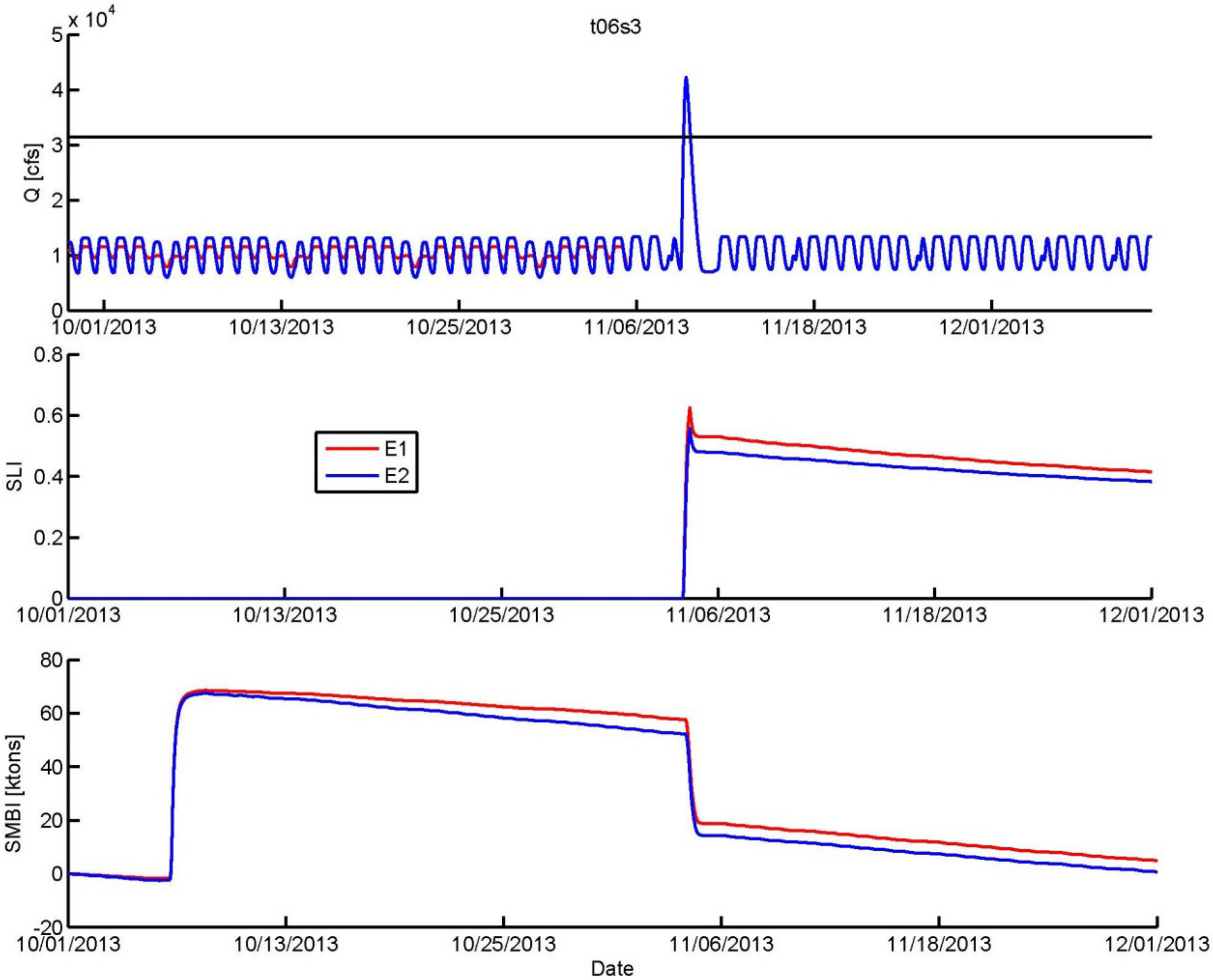

FIGURE E-25 Load-Following Curtailment Effects on SLI and SMBI (Although small effects are noticeable for the month after an HFE, by the end of the calendar year there is no difference in SLI and the difference in SMBI is 9 ktons.)

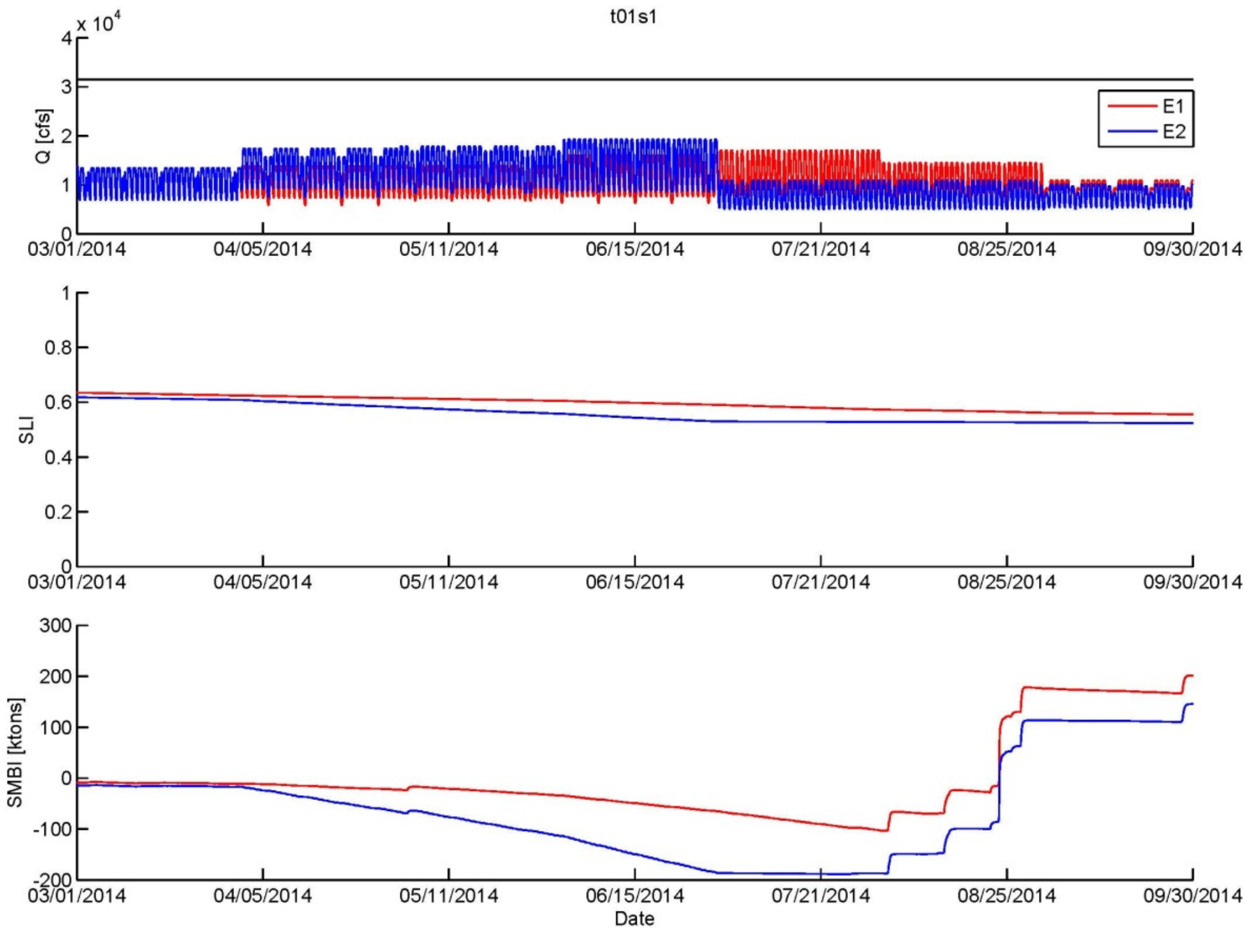

FIGURE E-26 Low Summer Flows for WY 2014, Hydrology Trace 1, Sediment Trace 1 (Long-term strategy E2 has low summer flows starting in July; this necessitates higher flows in April–June. Both SLI and SMBI are higher for alternative strategies without low summer flows [long-term strategy E1] than for those with low summer flows [long-term strategy E2].)

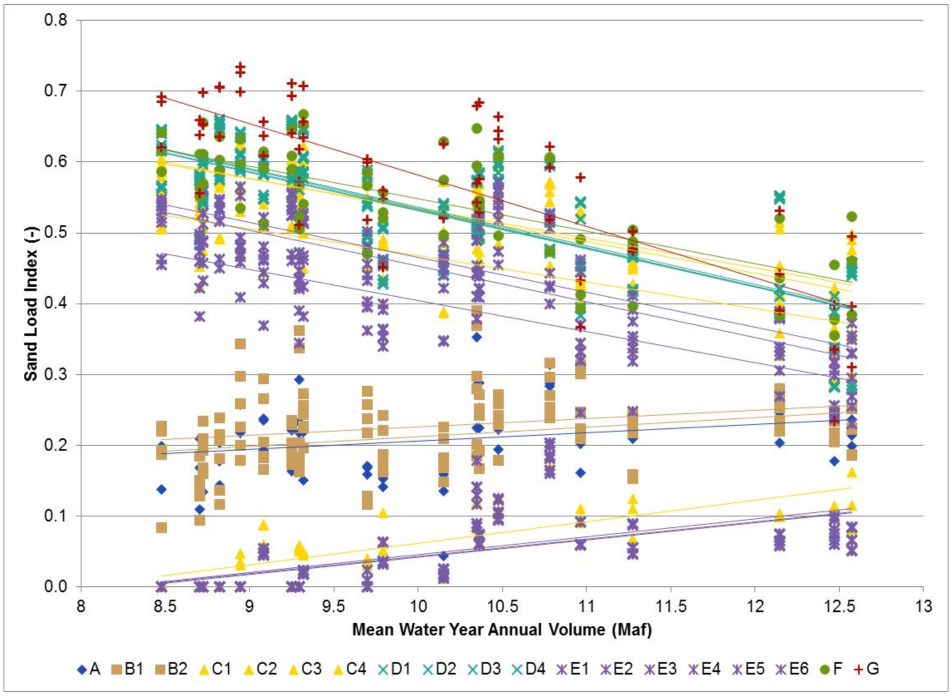

FIGURE E-27 Hydrology Impacts on the Sand Load Index (Wetter hydrological conditions tend to reduce SLI for long-term strategies without defined restriction on the number of HFEs that can be triggered [C1, C2, D1, D2, D3, D4, E1, E2, F, G]. Wetter hydrological conditions tend to increase SLI for long-term strategies with defined restrictions on the number of HFEs that can be triggered [A, B1, B2, C3, C4, E3, E4, E5, E6].)

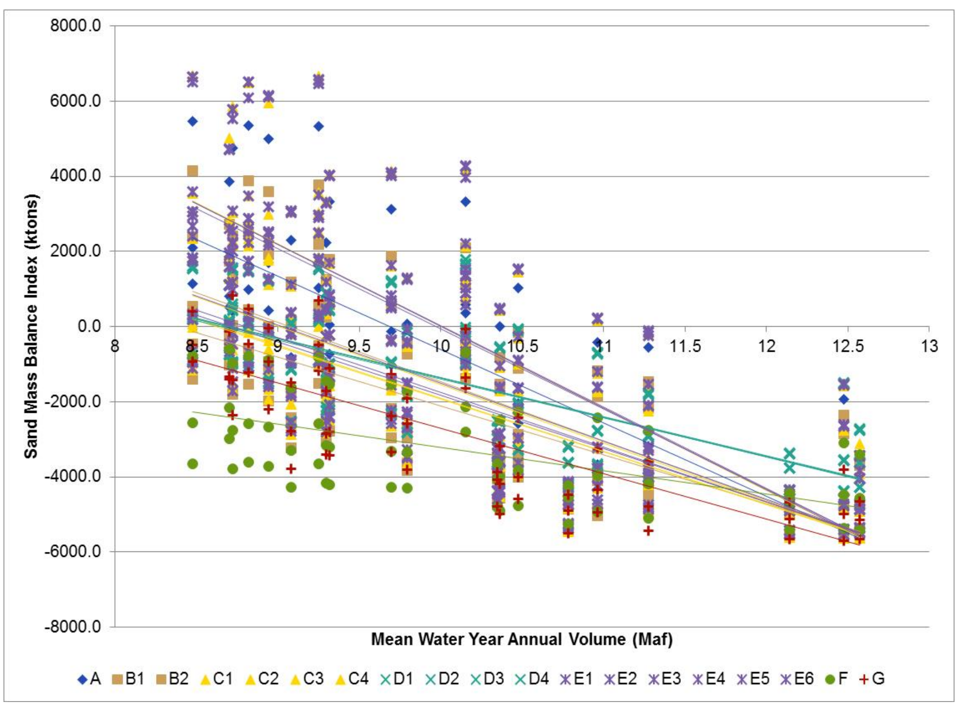

FIGURE E-28 Hydrology Impacts on the Sand Mass Balance Index (Wetter hydrological conditions create lower Sand Mass Balance Index values.)

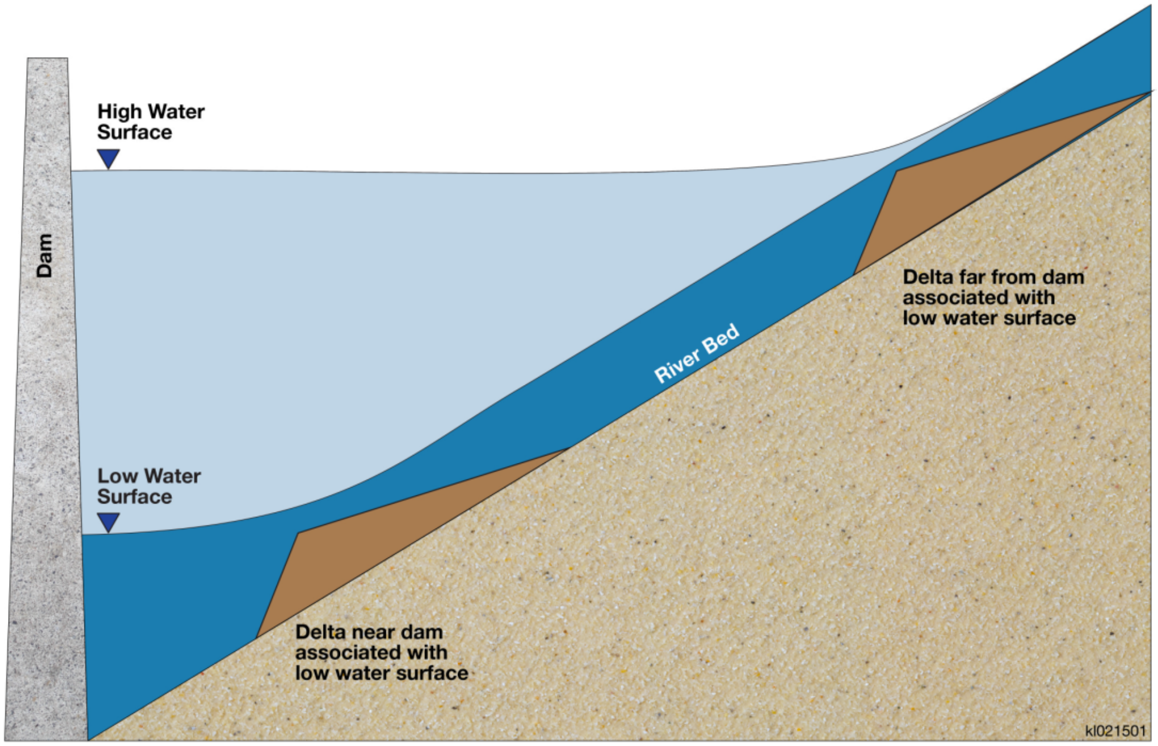

FIGURE E-29 Conceptual Diagram of Water Surface Elevation Affecting Delta Location

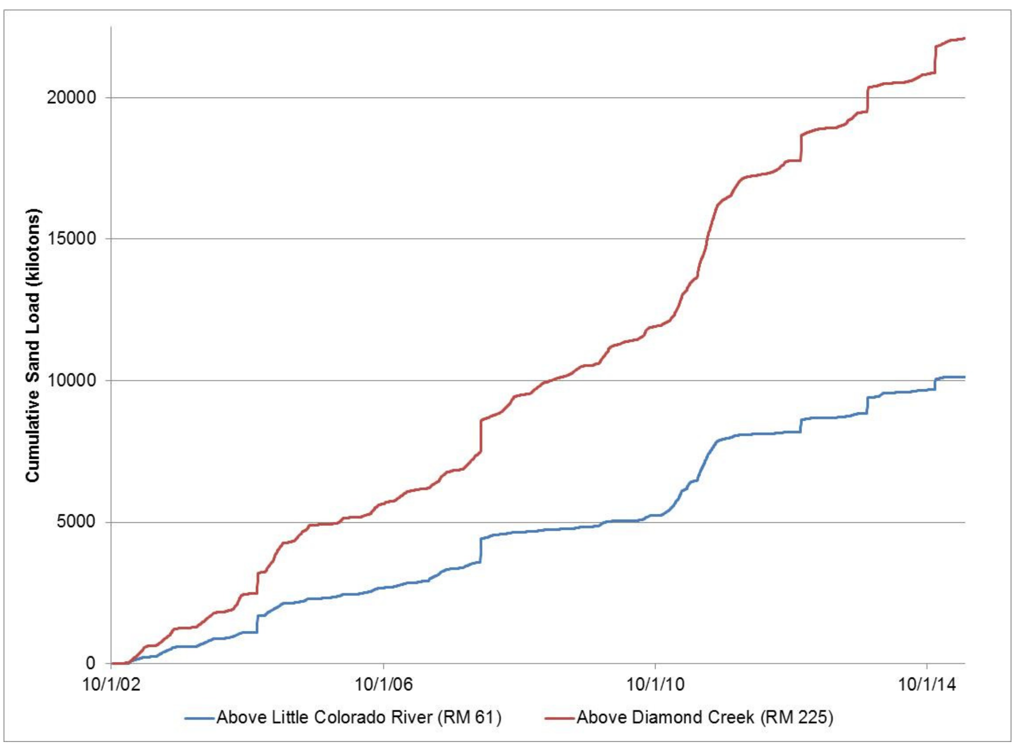

FIGURE E-30 Historical Cumulative Sand Load Leaving Marble Canyon (RM 61) and Reaching the Gage above Diamond Creek (RM 225) (Source: GCMRC 2015)

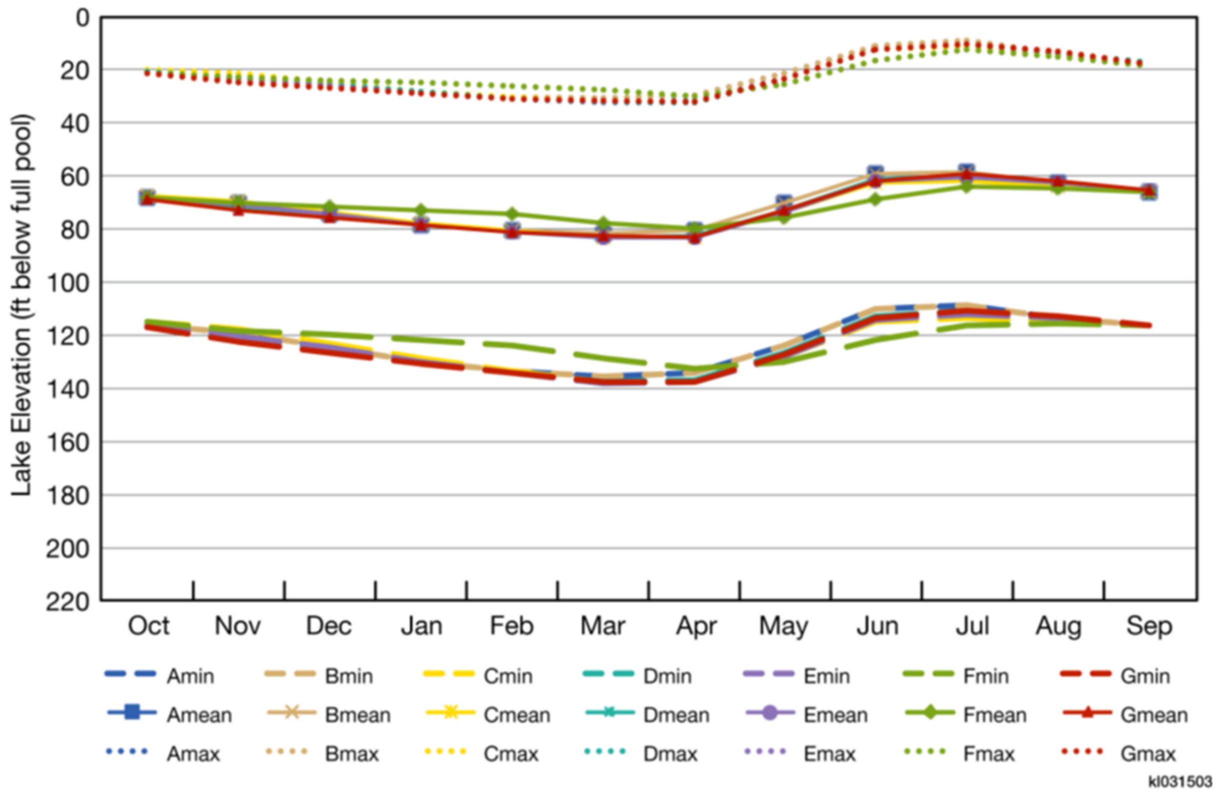

FIGURE E-31 Hydrology Impacts of Lake Powell Pool Elevations by Month across Alternatives

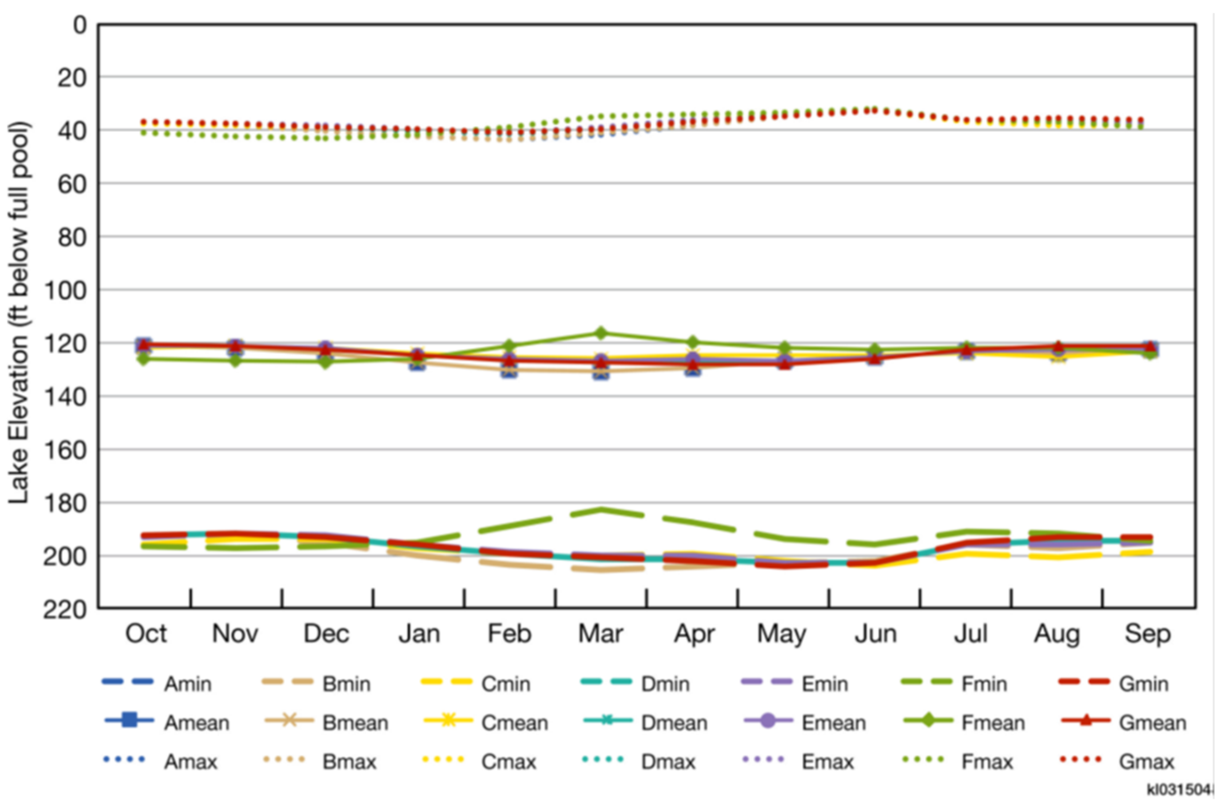

FIGURE E-32 Hydrology Impacts of Lake Mead Pool Elevations by Month across Alternatives

TABLE E-1 Sources for Historical Tributary Sediment Load Data

Tributary	Period of Record, by Source: Topping (2014)	Period of Record, by Source: GCMRC (2015)	Record Length
Paria River	10/1/1963 to 10/1/1996	10/1/1996 to 1/1/2014	50.3 years
Little Colorado River	10/1/1994 to 3/27/2013		18.5 years

TABLE E-2 Historical Periods Used for Paria Sediment Traces s1, s2, and s3

Sediment Trace	Sediment Accounting Periods	Simulation Period
s1	Fall 1981–Fall 2001	1/1/1981–12/31/2001
s2	Fall 1995–Fall 2013 : Spring 1964–Fall 1965	1/1/1995–11/30/2013 : 12/1/1963–12/31/1965
s3	Fall 2011–Fall 2013 : Spring 1964–Fall 1981	1/1/2011–11/30/2013 : 12/1/1963–12/31/1981

TABLE E-3 Historical Periods Used for Little Colorado River Sediment Traces s1, s2, and s3

Sediment Trace	Simulation Period
s1	1/1/1999–12/31/2012 : 1/1/1995–12/31/2001
s2	1/1/2007–12/31/2012 : 1/1/1995–12/31/2009
s3	1/1/2004–12/31/2012 : 1/1/1995–12/31/2006

TABLE E-4 List of HFEs Available for Sediment-Triggered Events (fall and spring)

HFE ID	Peak Discharge (cfs)	Duration at Peak (hours)
A	45,000	336
B	45,000	288
C	45,000	240 (Alternative G) 250 (Alternative D)
D	45,000	192
E	45,000	144
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

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