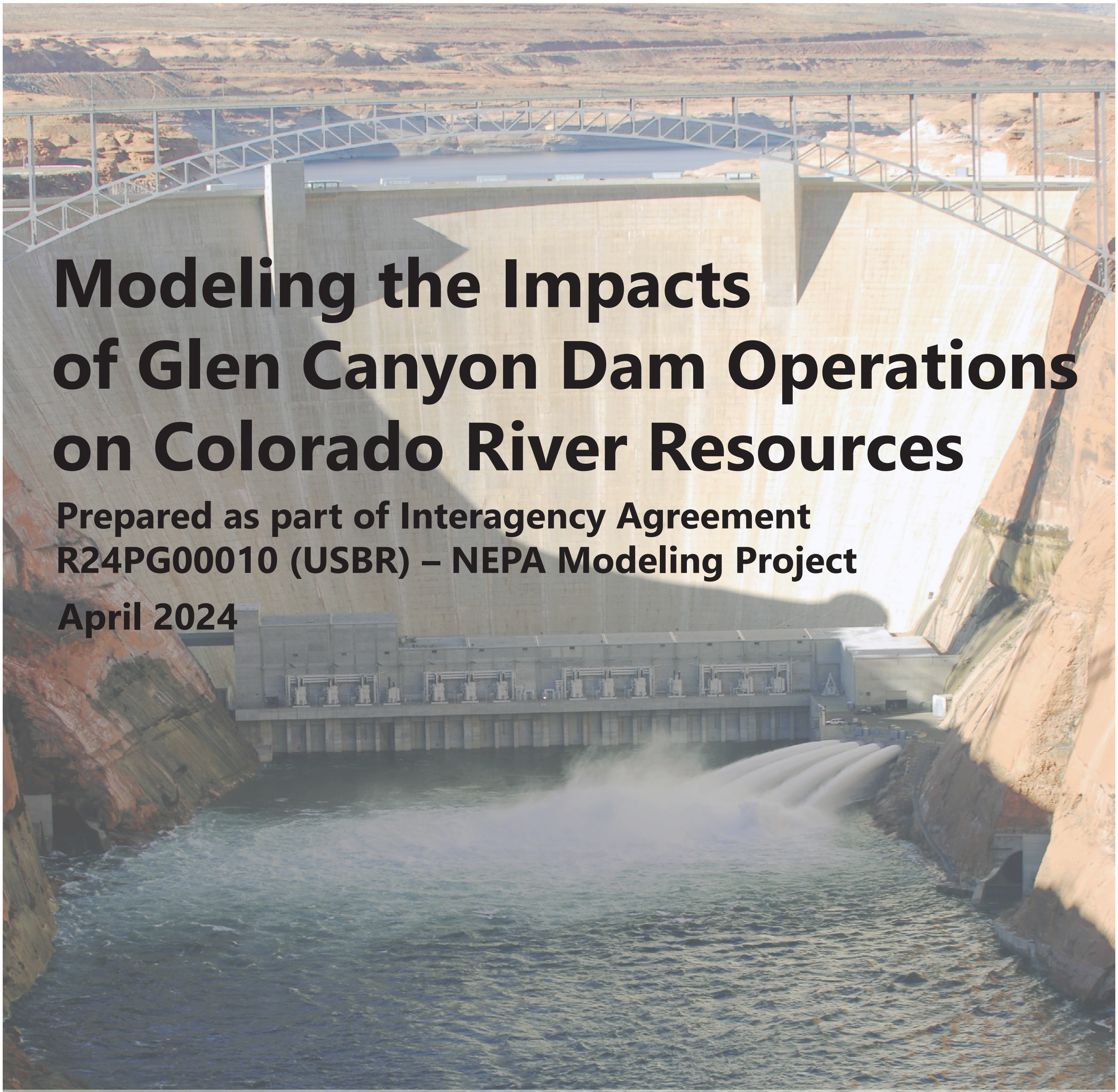
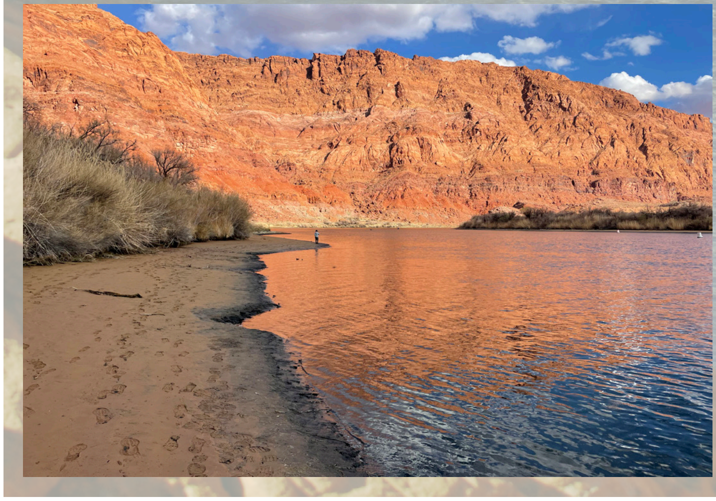


Modeling the Impacts of Glen Canyon Dam Operations on Colorado River Resources

Prepared as part of Interagency Agreement R24PG00010 (USBR) – NEPA Modeling Project

April 2024



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Suggested citation

Entire Report

Yackulic, C.B., Bair, L.S., Eppehimer, D.E., Salter, G.L., Deemer, B.R., Butterfield, B.J., Kasprak, A., Caster, J.J., Fairley, H.C., Grams, P.E., Mihalevich, B., Palmquist, E.C., and Sankey, J.B., 2024, Modeling the impacts of Glen Canyon Dam operations on Colorado River resources: Phoenix, Ariz., U.S. Department of Interior, Bureau of Reclamation, cooperator publication prepared by U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Flagstaff, Ariz., April 2024, 133 p.

Example Chapter within Report

Eppehimer, D.E., and Yackulic, C.B., 2024, Modeling impacts of different reservoir management scenarios on smallmouth bass (*Micropterus dolomieu*) entrainment and population growth rates, *in* Yackulic, C.B., and others, 2024, Modeling the impacts of Glen Canyon Dam operations on Colorado River resources: Phoenix, Ariz., U.S. Department of the Interior, Bureau of Reclamation, cooperator publication prepared by U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Flagstaff, Ariz., April 2024, p. 72-83.

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Photo credits, cover

Glen Canyon Dam, 2008: Anne Phillips, USGS (retired); Lees Ferry beach, 2021: Lucas Bair, USGS; Colorado River Mile ~212 looking upstream below Fall Canyon, 2007: USGS public domain.

Disclaimer

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Abbreviations

- Bureau of Reclamation (Reclamation)
- cfs: cubic feet per second (ft^3/s)
- CM: Cool Mix Alternative
- CM_FS: Cool Mix with Flow Spikes Alternative
- CM_FS_RM15: Cool Mix with Flow Spikes triggered by River Mile (RM) 15 water temperatures
- CM_FS_RM61: Cool Mix with Flow Spikes triggered by River Mile (RM) 61 water temperatures
- CM_RM15: Cool Mix triggered by River Mile (RM) 15 water temperatures
- CM_RM61: Cool Mix triggered by River Mile (RM) 61 water temperatures
- CS: Cold Shock Alternative
- CS_FS: Cold Shock with Flow Spikes Alternative
- CS_FS_RM15: Cold Shock with Flow Spikes triggered by River Mile (RM) 15 water temperatures
- CS_FS_RM61: Cold Shock with Flow Spikes triggered by River Mile (RM) 61 water temperatures
- CS_RM15: Cold Shock triggered by River Mile (RM) 15 water temperatures scenario
- CS_RM61: Cold Shock triggered by River Mile (RM) 61 water temperatures scenario
- CPUE: catch-per-unit-effort
- CR: Colorado River
- CRe: Colorado River ecosystem
- CRFS: Colorado River Flow and Sediment
- CRMMS: Colorado River Midterm Modeling System
- CRSS: Colorado River Simulation Study
- DO: dissolved oxygen
- EGC: Eastern Grand Canyon
- EIS: Environmental Impact Statement
- ESP: ensemble streamflow prediction
- Fasl: feet above sea level
- ft^3/s: cubic feet per second (cfs)
- GCD: Glen Canyon Dam
- GCDAMP: Glen Canyon Dam Adaptive Management Program
- GCMRC: Grand Canyon Monitoring and Research Center
- GCNP: Grand Canyon National Park
- HBC: humpback chub (*Gila cypha*)
- HFE: High Flow Experiment

- Interim Guidelines SEIS: Near-term Colorado River Operations Supplemental Environmental Impact Statement
- kaf: thousands of acre feet
- LCR: Little Colorado River
- LMC: Lower Marble Canyon
- LTEMP EIS: Long-term Experimental and Management Plan Environmental Impact Statement
- LTEMP EIS ROD: Long-term Experimental and Management Plan Environmental Impact Statement Record of Decision
- LTEMP SEIS: Long-term Experimental and Management Plan Supplemental Environmental Impact Statement
- maf: million-acre feet
- m/s: meters per second
- MWh: megawatt hours
- NA: No Action Alternative
- NB: Non-Bypass Alternative
- NED: National Elevation Database
- NW: new HFE window only alternative
- PA: Proposed Action Alternative
- RM: River Mile (used in the Colorado River, by convention)[1]
- Rkm: river kilometers (used in the Little Colorado River, by convention)
- SMB: smallmouth bass (*Micropterus dolomieu*)
- SEIS: Supplement to an Environmental Impact Statement
- SRM: Sand Routing Model
- Tmt: thousand metric tons
- UMC: Upper Marble Canyon
- WAPA: Western Area Power Administration

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[1] River miles (RM) for the Colorado River are negative from Glen Canyon Dam (begins at -15 RM) downstream to Lees Ferry (0 RM) and then positive thereafter to upper Lake Mead (about RM 305).

Introduction

This introduction is largely taken from that provided in Interagency Agreement R24PG00010 (Yackulic and others, 2024).

The Bureau of Reclamation (Reclamation) has published a final supplemental Environmental Impact Statement (SEIS) for near-term Colorado River operations (Bureau of Reclamation, 2024a), and has published a draft and is writing a final SEIS for the Long-Term Experimental and Management Plan (LTEMP; Bureau of Reclamation, 2024b). These actions have the potential to affect downstream resources, including threatened and endangered species, in the Grand Canyon, Arizona, USA.

This report covers modeling support provided for the two SEIS by the Grand Canyon Monitoring and Research Center (GCMRC; U.S. Geological Survey, Southwest Biological Science Center).[2] The first SEIS, the Near-term Colorado River Operations Supplemental Environmental Impact Statement (Interim Guidelines SEIS; Bureau of Reclamation, 2024a) modifies the U.S. Department of the Interior’s 2007 Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead (U.S. Department of the Interior,, 2007) that determines annual water releases from GCD based on inflow to Lake Powell, the power generating requirements of GCD, and relative reservoir levels of Lake Powell and Lake Mead (Bureau of Reclamation, 2024a). Drought conditions have lowered the elevation of Lake Powell and may require GCD to release less water than was analyzed in the Interim EIS (7 million acre-feet [maf]/year). The effect of less water released, as well as lower reservoir levels and associated water quality concerns, on downstream resources was not analyzed in the 2007 Interim Guidelines EIS. Reclamation requested GCMRC support to provide models predicting the effects to resources of water releases lower than 7 maf/year, including models predicting effects to threatened and endangered species for use in a Biological Assessment.

The second SEIS, the Glen Canyon Dam Long-Term Experimental and Management Plan Supplemental Environmental Impact Statement (LTEMP SEIS; Reclamation, 2024b) modifies Reclamation’s GCD Long-Term Experimental and Management Plan Environmental Impact Statement (U.S. Department of the Interior, 2016). This SEIS provides an adaptive management framework for GCD operations through 2036 that includes dam operations (monthly, daily, and hourly release patterns), non-flow actions, and experimental and management actions (U.S. Department of the Interior, 2016). The LTEMP SEIS modifies the existing analysis to 1) review and develop flow options to disadvantage smallmouth bass (including modeling hydropower

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[2] Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

revenue under differing flow models), and 2) change the sediment accounting period and triggers for High Flow Experiments (HFEs) in the existing EIS (Bureau of Reclamation, 2024b). These two changes may alter effects to downstream resources and were not adequately modeled in the original LTEMP EIS and Biological Assessment (Bureau of Reclamation, 2024b).

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I. Modeling of Monthly Hydrology and Designer Flow Implementation under Different Reservoir Management Scenarios

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GERARD SALTER, U.S. GEOLOGICAL SURVEY

Background – Interim Guidelines SEIS

The Interim guidelines supplemental Environmental Impact Statement (SEIS) considered two alternatives (Bureau of Reclamation, 2024a). Under the No Action Alternative, the existing agreements that controlled operations of Glen Canyon and Hoover Dams continued to guide releases through the 2026 operation year. The Proposed Action alternative included increased water conservation tied to Lake Mead reservoir elevations and changes to Glen Canyon Dam (GCD) releases under certain conditions that could lower annual volume to as low as 6.0-million-acre feet (maf; see Interim Guidelines SEIS for more details). The Bureau of Reclamation produced 90 hydrologic traces under each alternative to allow for modeling of potential impacts (Bureau of Reclamation, 2024a). These 90 hydrologic traces were based on the June 2023 ensemble streamflow predictions (ESP) forecast (a set of 30 traces based on the last 30 years of observed hydrology) and included the official 100 percent ESP, along with 90 percent ESP and 80 percent ESP to represent the potential for drier conditions that have been observed over the last 30 years (Bureau of Reclamation, 2024a).

Background – LTEMP SEIS

The remainder of this section of the report describes the process used to forecast monthly reservoir elevations and hydrologic conditions for 30 hydrologic traces under 11 flow scenarios representing 7 flow alternatives considered by Reclamation as part of their Long-Term Experimental and Management Plan Supplemental Environmental Impact Statement (LTEMP SEIS). As with the Interim Guidelines SEIS analysis, we relied on the June 2023 ensemble streamflow predictions (ESP). At the time of modeling, no decision had been made regarding the Interim Guidelines SEIS so we assumed the No Action hydrologic conditions from the Interim Guidelines hydrologic modeling as a baseline for reservoir elevations and annual volume releases. Furthermore, as the LTEMP SEIS considers several alternatives, we focused analyses on the 30 traces under the official 100 percent ESP to allow for efficient comparison of alternatives in a timely fashion. Understanding these flow alternatives (as well as scenarios within flow alternatives) requires some basic understanding of the geography of the Grand Canyon and of the infrastructure within Glen Canyon Dam, which we describe before detailing the alternatives.

GCD releases water from Lake Powell into a segment of the Colorado River colloquially referred to as the Lees Ferry reach that has been managed for most of the last half-century as a blue-ribbon rainbow trout fishery. This river segment extends approximately 15.6 river miles (RM; 25 river kilometers) from the base of GCD to the confluence of the Colorado River with the Paria River just below Lees Ferry that demarcates the division between the Upper and Lower basins of the Colorado River according to the Colorado River compact (Schmidt and others, 2022). The location Lees Ferry is commonly defined as River Mile 0 (RM 0), with negative river miles referring to distance upstream from Lees Ferry and positive river miles referring to distance downstream. Many of the flow alternatives proposed by Reclamation are designed to have flexibility to be triggered by water temperatures anywhere from RM 15 (i.e., ~50 river kilometers [rkm] downstream from the dam) to near the confluence with the Little Colorado River near RM 61 (~125 rkm downstream from the dam) (Bureau of Reclamation, 2024b). High Flow Experiments (HFEs) are triggered based on the sand mass balance in the river segment between the Colorado-Paria confluence and the Colorado-Little Colorado River confluence (often referred to as Marble Canyon) (Bureau of Reclamation, 2024b).

Since completion, GCD has released most water through penstocks centered on an elevation of 3470 feet above sea level (fasl), with occasional releases through river outlet tubes located at 3370 fasl, primarily during HFEs; however, many of the flow alternatives being considered by Reclamation involve increased releases through the river outlet tubes to cool the overall temperature of reservoir releases (Bureau of Reclamation, 2024b). During the late Spring through Fall months, water in the upper layers of Lake Powell warms creating a temperature gradient from the warm epilimnion layer through a transition zone known as the metalimnion, reaching the cold hypolimnion layer at deeper depths, which shows minimal seasonal variation in water temperature. As reservoir elevations have declined over the 21st century, water drawn through the penstocks has increasingly pulled from shallower depths within the reservoir leading to substantial warming of releases from Lake Powell (Dibble and others, 2021; Eppehimer and others, 2024). Water drawn through the river outlet tubes, located 100 feet deeper, is typically much colder during summer and fall months. Some of the alternatives being considered manage water temperature through manipulating the proportion of water being released from penstocks versus river outlet tubes.

Proposed flow alternatives are triggered by a temperature threshold of 15.5 °C at the target location. A 16 °C daily average water temperature spawning initiation threshold is typically observed for smallmouth bass (SMB [*Micropterus dolomieu*]; Eppehimer and others, 2024), and is assumed for this modeling (see Chapter IV for more details). The target of 15.5 °C was chosen to account for variation in water temperature releases and warming rates and increases the likelihood that water temperature would remain near or below 16 °C at the target river mile. The alternatives are designed to be flexible to have target locations between RM 15 and RM 61. For each of these alternatives we analyzed two scenarios – one in which the target location was located at RM 15 and another where the target location was located at RM 61.

Reclamation is analyzing seven flow alternatives in the LTEMP SEIS (Bureau of Reclamation, 2024b):

1) The first flow option is a **No Action Alternative** that includes no changes to the sediment accounting window (i.e., continuation of separate Fall and Spring sediment accounting windows) and no flows specifically designed to prevent warmwater nonnative fish establishment. Under this alternative, Fall HFE triggers and duration are based on the sand mass balance over the period of July 1st to November 30th, and Spring HFE trigger and duration are based on the sand mass balance over the period December 1st to June 30th. If HFEs are triggered, but not implemented there is no rollover of sediment mass balance.
2) The remaining six flow alternatives all include a change to a one-year sediment accounting window, however the second flow alternative, **change to sediment accounting window only**, only includes this change (i.e., it does not include any flows specifically designed to prevent warmwater nonnative fish establishment). The Fall and Spring sediment accounting windows are merged into a single one-year window, allowing decision-makers the flexibility to delay an HFE from Fall until Spring. HFE trigger/duration is selected based on modeled sand mass balance between July 1st and the end of the HFE (Fall or Spring). If an HFE is triggered but not implemented, a positive sand mass balance is carried forward into the next accounting period. Modeling assumptions include: 1) Spring HFE implementation is preferred to Fall, and an HFE would be delayed to Spring if duration is within one duration tier (i.e., 12, 24, 36, 48, 60, 72, 96, 144, 192, or 250 hours), and 2) no HFEs implemented below 3500 fasl, and water volume may be borrowed from other months to the implementation month to avoid violating LTEMP minimum flow constraints.
3) The third flow alternative, **Cool Mix**, is triggered when predicted daily water temperatures at a target location are greater than or equal to 15.5 °C without the action and involves mixing releases from penstock and river outlet tubes to obtain a predicted average daily water temperature less than 15.5 °C at the target location. The target of 15.5 °C was chosen to account for variation in water temperature releases and warming rates and increase the likelihood that water temperature would remain near or below 16 °C at the target river mile. This alternative, as well as the

fourth, fifth, and sixth alternatives, are designed to be flexible to have target locations between RM 15 and RM 61 and for each of these alternatives we analyzed two scenarios – one in which the target location was located at RM 15 and another where the target location was located at RM 61.

4) The fourth alternative, **Cool Mix with Flow Spikes**, is also triggered when predicted daily water temperatures at a target location are greater than or equal to 15.5° C without the action. The target of 15.5 °C was chosen to account for variation in water temperature releases and warming rates and increase the likelihood that water temperature would remain near or below 16 °C at the target river mile. In addition to a cool mix as described for the third alternative, the alternative also uses flow spikes, that is, short duration increases to the maximum attainable discharge through both river outlet and penstocks with up and down ramp rates within LTEMP guidelines and eight hours at the peak discharge. Flow spikes are intended to disturb marginal side habitats (e.g., backwaters or the feature at ~RM -12 often referred to as the slough) by increasing velocities to sweep larvae from underneath male SMB and disrupt spawning behavior. Flow spikes are only triggered in the months of May through August when the potential for warming in marginal side habitats is greatest. A flow spike could be replaced by an HFE if doing so would maximize benefits to sediment and is timed appropriately to affect SMB spawning. The first flow spike is replaced by an HFE if an HFE would be triggered by sediment conditions.

5) The fifth alternative, **Cold Shock**, attempts to disrupt spawning by dropping water temperature to below 12° C for a 48-hr period or as cold as possible if 12° C is not attainable; however, a minimum of 2,000 cubic feet per second (cfs) hydropower would be maintained during the cold shock. The 48-hr cold shocks would occur when there are lowest impacts to hydropower, and therefore would likely fall on weekends. Cold shocks are triggered when the predicted average daily water temperature is greater than or equal to 15.5° C at the target location and occur once a week for the first 12 weeks after triggering. The target of 15.5 °C was chosen to account for variation in water temperature releases and warming rates. Within a month, the amount of bypass calculated for cold shocks was the minimum required (tested in half-tube increments) to lower temperature below 12 °C at the targeted river mile in all weekends or 12,600 cfs if a lesser volume did not meet this condition. Hydropower releases were always assumed to be 2,000 cfs during the Cold Shock.

6) The sixth alternative, **Cold Shock with Flow Spikes**, includes cold shocks as in the fifth alternative, but also adds flow spikes directly after the cold shocks. Up to three 8-hour flow spikes might occur. These were modeled as two in first month and one in subsequent month (in the first, third and fifth weeks after cold shocks are triggered).

Flow spikes occur as described above in the fourth alternative. Flow spikes were only modeled to occur in May, June, July, or August. In weeks with flow spikes, the cold shock would occur before the flow spike.

7) The seventh flow alternative, the **Non-Bypass Alternative**, only uses bypass during HFEs. When predicted average daily water temperature is greater than or equal to 15.5 °C at RM 61, this alternative creates once a week fluctuation in discharge using only hydropower releases. The target of 15.5 °C was chosen to account for variation in water temperature releases and warming rates. Specifically, flow is first dropped to 2,000 cfs for four hours and then increased to the maximal attainable discharge through the hydropower outlets (based on Lake Powell elevation) for four hours before returning to normal operations. Note that the Non-Bypass Alternative specifically refers to management of SMB. Bypass tubes may still be used for HFEs if an HFE trigger occurs.

One important feature to note is that modeling of each alternative involves some simplifying assumptions. HFEs can occur on any day of the month, but for modeling purposes they occur on the 15th of the month. Similarly, if flows designed for SMB are implemented in the future, it is likely they will be designed at a weekly scale, however they were modeled at a monthly scale here. Differences among weeks in a month are typically greatest during June and early July when the temperature profile in Lake Powell is developing. Whereas it is straightforward for the SMB model to predict bypass at a daily or weekly scale that would require running multiple instances of hydropower maximization within each month in Chapter II. Therefore, we instead chose to post-process daily bypass estimates from the SMB model such that flows were simulated to occur all month long if SMB flows were triggered before or at the halfway mark of a month and simulated to start in the subsequent month if SMB flows were triggered after the hallway mark of a month. Furthermore, all days within a month were simulated to have the same bypass which was calculated as equal to the median of the month (rounded up to the higher value if a month had 28 or 30 days and exactly half of days were at one value and the other half at another value). Comparison of total bypass between raw and post-processed output suggested minimal change to overall bypass across all 30 traces with the amount of bypass subtly increasing in some traces and decreasing in other traces.

Workflow and Modeling Details to Produce LTEMP SEIS Monthly Hydrologies

Generating monthly reservoir elevations and releases under different management scenarios and hydrologic conditions required adopting a workflow that accounted for the interdependencies between different decisions.

Results of this workflow were tracked in spreadsheets that were later converted to csv files for the data release associated with this report (Yackulic and others, 2024).

An important feature of the workflow is that the 11 scenarios can be viewed as the consequence of a series of model decisions such that multiple scenarios may be represented by a single spreadsheet during early steps of the workflow (Figure 1-1).

Our workflow began by selecting a set of hydrologic traces. Specifically, we used a set of 30 ensemble streamflow predictions (ESP; 100% ESP set) at a monthly time step over 4 years to characterize a range of potential hydrologic conditions (Yackulic and others, 2024). These 30 traces are a subset of the traces analyzed in the Interim Guidelines SEIS under the No Action Alternative (Bureau of Reclamation, 2024a) and include monthly elevations for Lake Powell in units of feet above sea level, as well as monthly inflows and monthly outflows in units of thousands of acre feet (kaf). Some of our models required additional months of elevations, inflows, and outflows beyond the data originally provided by Reclamation (Bureau of Reclamation, 2024a only includes hydrologic data through September 2027), so we made the same assumptions regarding inflow and outflow in the months between October 2027 – April 2028 regardless of the hydrologic trace and management scenarios. Specifically, we assumed 8 maf annual inflows into Lake Powell following monthly volumes determined by a log transformed linear model fit to 2000-2021 historic inflows, and we assumed 7.48 maf annual outflows from Lake Powell with monthly volumes determined by LTEMP EIS guidelines. Based on the elevation specific to each hydrologic trace in September 2027, we then calculated monthly elevations for October 2027 to April 2028 using the Colorado River Simulation Study (CRSS: Schuster, 1998; Wheeler and others, 2019) water balance equation.

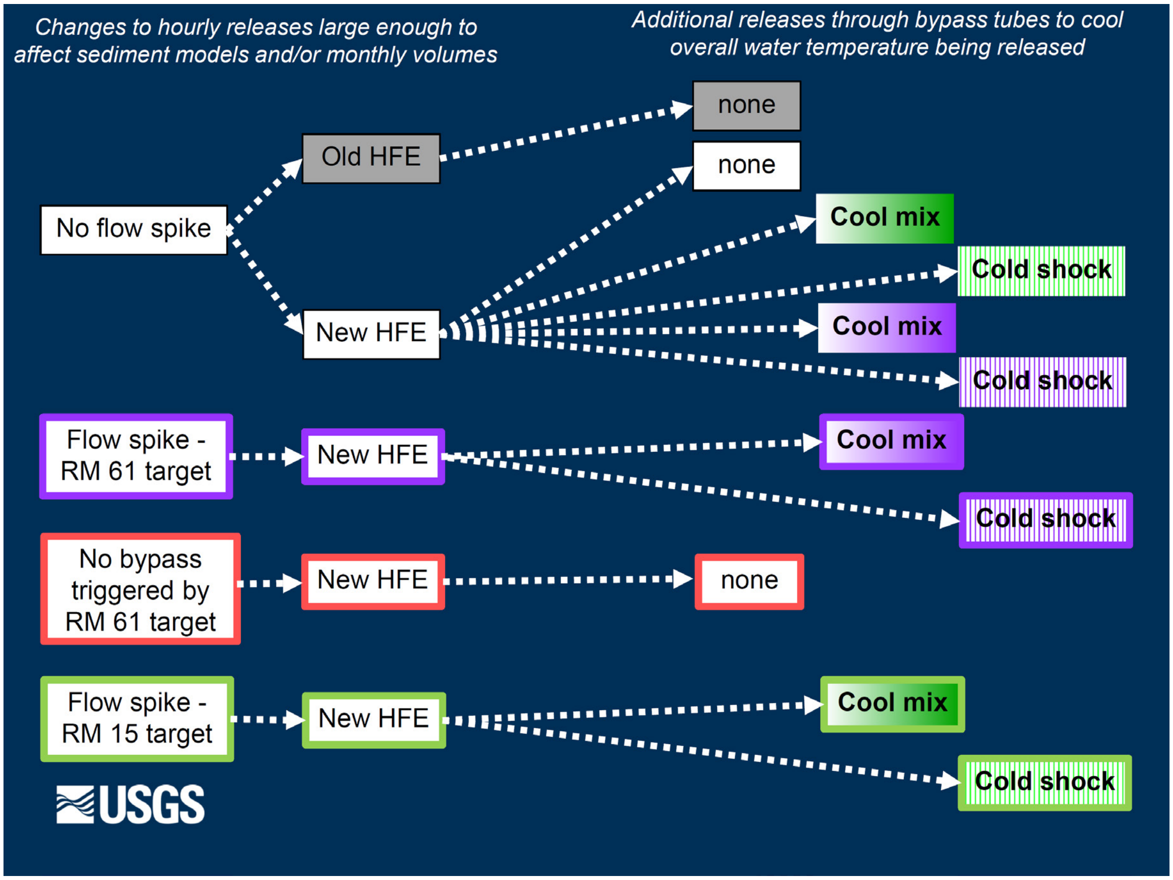

Figure 1-1. Overview of workflow used to represent eleven management scenarios (boxes on the right-hand side of figure) as a consequence of a series of modeling steps. The grey boxes represent the No Action Alternative. The white boxes represent the change to sediment accounting window only alternative. All alternatives that involve flows designed for SMB include color. Scenarios in which temperatures at RM 61 triggered flows are colored purple if they include bypass and red if they do not. Scenarios in which temperatures at RM 15 triggered flows are colored green. Scenarios that include flows intended to disturb SMB spawning have bold edges. Cool mix scenarios include a color ramp, while cold shock scenarios include vertical lines.

Next, in step 2 of our workflow, we determined for each hydrologic trace whether a flow spike or the non-bypass flow fluctuations would be triggered based on water temperature predictions from the water temperature model embedded in the SMB model (see Chapter IV) and described in Eppehimer and others (2024). This model is implemented in R statistical software (R Core Team, 2021). When flow spikes were triggered was modeled separately based on predicted water temperatures at RM 15 and RM 61. Results of this analysis were stored in a worksheet with integer values indicating whether 2, 1, or 0 flow spikes were predicted to occur in a particular trace and month. Non-Bypass flow fluctuations were modelled based only on water temperatures at RM 61. Results of this analysis were also stored in an output file.

We choose these two sets of fluctuating flows first because the changes in hourly releases associated with these flows are large enough to significantly impact sand mass balance and/or to require adjustments to monthly release volumes.

In step 3, we then modeled the triggering of HFEs in Matlab (The MathWorks Inc., 2022) using models previously developed for the Grand Canyon and described in Chapter III. The New HFE protocol (with a single sediment accounting window) was applied to each of the four spreadsheets developed in step 2, however, the current (old HFE in Figure 1-1) was only applied to the scenario without any flows designed specifically for SMB (i.e., no flow spike in Figure 1-1). Output from Step 3 included the magnitude of both HFEs and flow spikes (which depend on reservoir elevations) in cfs, as well as the duration of the HFEs in units of hours and revised monthly release volumes in units of thousands of acre feet of water (kaf).

Next, in step 4, we used water mass balance equations to adjust monthly reservoir elevations to align with the revised monthly volumes. These analyses were implemented in R statistical software (R Core Team, 2021) and results were stored in a new worksheet. The No Action, change to sediment accounting window only, and Non-Bypass Alternatives were complete after this step.

For cold shock and cool mix scenarios, an additional step was required in which the SMB model (see Chapter IV) was run in R statistical software (R Core Team, 2021) to determine the amount of bypass (flow through the river outlet works) required to meet the specifications of the flow alternatives at the target river mile. For modeling of alternatives that used cool mix or cold shock, we assumed river outlet tubes could be operated at ½ tube increments and that each tube had a capacity of 3,150 cfs. Furthermore, the code was written to choose the minimum amount of bypass to meet the requirements of the particular flow alternative in each month in which the flow alternative was triggered. The amount of bypass was reported in units of cfs which apply either to all days and hours in a month (in the case of the cool mix scenarios) or to the 48-hour period of the cold shock scenarios. The amount of bypass discharge required under cold shock or cool mix scenarios were reported in a worksheet in units of cfs.

Data Availability Statement:

Data generated during this study are published and available (Yackulic and others, 2024).

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II. Modeling the Energy Generation and Economic Value of Glen Canyon Dam Releases

LUCAS BAIR, U.S. GEOLOGICAL SURVEY, CHARLES YACKULIC, U.S. GEOLOGICAL SURVEY

Introduction

The Glen Canyon Dam (GCD) powerplant is connected to the Western Power Grid through a regional transmission system and provides electricity to utilities in a 15-state region of the western United States. The objective of modeling energy costs of GCD Releases is to produce hourly flow, generation, and economic value estimates over the planning horizon for each alternative and hydrologic traces in the Long-term Experimental and Management Plan Supplemental Environmental Impact Statement (LTEMP SEIS). The results are used to quantitatively analyze the economic impacts from each alternative in the LTEMP SEIS. The models are based on standard energy economic analysis methods (Harpman, 1999).

The proposed alternatives in the LTEMP SEIS include a new sediment accounting window and managing Colorado River water temperature downstream of GCD from May through October. Therefore, altered flows would not be implemented during the winter months, and there would be little effect on energy generation during this timeframe. The following analysis focuses on warm-weather months when flows could be implemented under the proposed action with options.

Compared with current conditions, five of the seven flow options would include passing more water through the bypass tubes where energy is not generated. Energy generation effects would vary, depending on the flow option implemented. Each flow would impact hydropower by reducing the energy generation and increasing the amount of replacement energy required to meet demand in the interconnected electricity sector.

Methods

The estimated costs of changes in energy generation at GCD were developed using a standard constrained optimization model. The constrained optimization model optimizes electricity production based on a specified objective, water availability, and operating constraints. Modeling was conducted for the planning horizon, October 2023 through November 2027.

Monthly operating priorities are based on average historic hourly releases at GCD from September 2020 through August 2023. The assumption is made that the recent operation at GCD is a reasonable representation of Western Area Power Administration’s attempt to meet near-term scheduling requests by utilities.

Operation at GCD was optimized using these release data (Bureau of Reclamation, 2024) to prioritize hourly operation within a representative week, constrained by the operational constraints in the Long-term Experimental and Management Plan Record of Decision (LTEMP ROD; U.S. Department of Interior, 2016).

Our hydropower optimization model closely follows Harpman (1999). The hydropower objective is to identify the load following path that maximizes the opportunity to meet scheduling of hydropower generation:

$$\max_{v_1,\ldots,v_T} \sum_{t=1}^{T} w_t * energy(v_t, elev_t), \tag{1}$$

where v_t is the fixed flow cubic feet per second (cfs) through GCD over an hour (t), w_t is the weighted historic scheduling of energy generation at time t, $elev_t$ is the end of month reservoir elevation (feet above mean sea level) at time t, T is total time, and $energy(\cdot)$ denotes the energy production function, specified in equation 2.

Hydropower production in megawatt hours (MWh) generated at the GCD is a function of flow v_t through the turbines and reservoir elevation $elev_t$, both of which are assumed to be constant over an hour time step t, and α and β are estimated coefficients (Waldo and others, 2021):

$$energy(v_t, elev_t) \; = \; -\alpha \; * \; \beta(elev_t) * v_t, \tag{2}$$

Hydropower production is subject to several operational constraints, such as the amount of water available for release, maximum and minimum flow constraints, and ramp constraints. Our optimization model is subject to the following constraints, as specified in the LTEMP ROD (U.S. Department of Interior, 2016)

$$\begin{aligned}
&\textstyle\sum_{t\in m} v_t \le \text{max monthly volume (cfs)} && \text{for } m \in \{\text{month}\}\\
&v_t{=}j \ge \text{min off-peak flow} && \text{for } j \in \text{off-peak hours}\\
&v_t{=}i \le \text{min on-peak flow} && \text{for } i \in \text{on-peak hours}\\
&v_t \le \text{max flow} && \qquad (3)\\
&v_t{-}1 - v_t \le \text{max down ramp} &&\\
&v_t - v_t{-}1 \le \text{max up ramp} &&\\
&v_t - v_t{-}h \le \text{max flow change in 24-hours for} && h \in \text{24-hour period}
\end{aligned}$$

We post process the optimal hydrograph based on flow specifications in the LTEMP SEIS alternatives. For example, if flow spikes are implemented for a month in an alternative and hydrologic trace, those flow constraints are imposed on the baseline hydrograph, staying true to the constraints specified in the LTEMP ROD (U.S. Department of the Interior, 2016).

To forecast the economic value of energy generated at GCD, we developed models that predict marginal prices given industry forecasts of price (i.e., ARGUS Forward Mid-Market Power Curves: Argus Media, 2024). While these industry forecasts include important information on changing energy markets, they also include a risk premium that leads to systematic overestimation of future marginal prices (Benth and others, 2008; Office of Management and Budget, 2023) so use of these raw forecasts is likely to lead to systematic overestimation of differences among alternatives. We treated observed hourly historic locational marginal price at the Palo Verde Hub from February 2020 to August 2023 (California Independent System Operator, 2024) as data since many (but not all) users of power from Glen Canyon trade at this hub. We assumed that the relationship between ARGUS Forward Mid-Market Power curves (forecasts) and observed data would vary by month, day of week, and hour of the day such that each month of the year should have 168 independent models (one for each hour in each day of the week). Each of these models was a linear regression of the form: $\mathrm{Y} = \mathrm{a} + \mathrm{b}^*\mathrm{X}$, where X was the forecasted off-peak power price and Y was the observed location marginal price and a and b were estimated coefficients. We also tested using on-peak forecasts as a predictor but found that they did a poorer job of predicting relative changes in observed prices than off-peak forecasts (based on comparison of competing models via Akaike Information Criterion). While our X was off-peak, forecasts of the value of b varied dramatically based on the hour and day of the week allowing for accurate predictions. Values of a and b for each month, day, and hour were then combined with Argus Forward Mid-Market Power Curves for October 2023 through November 2027 (Argus Media, 2024) to predict prices over the period of LTEMP SEIS.

The economic cost of foregone energy generation of implementing an alternative is the difference between hydroelectricity economic value under the optimal load following path (No Action Alternative) and hydroelectricity economic value under an action alternative.

Results

Results are the hourly releases from GCD (cfs), generation (megawatt hours [MWh]) and economic value (nominal dollars) for each month, alternative, and hydrologic trace in the LTEMP SEIS (Bair and Yackulic, 2024).

Data Availability Statement:

Data generated during this study are published and available (Bair and Yackulic, 2024).

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III. Modeling Impacts of Different Reservoir Management Scenarios on Sediment Resources

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Background and Methods

Sandbars are a natural feature of the Colorado River and are important for recreation, habitat, and preservation of cultural resources. The construction of Glen Canyon Dam (GCD) is estimated to have reduced the sand load at the upstream end of Grand Canyon National Park by ~95%, and by the early 1970s was recognized to have caused net-erosion of sandbars in Grand Canyon (Topping and others, 2021). Decades of work led to the current protocol for sediment management in Grand Canyon, which involves the use of controlled floods known as High Flow Experiments (HFEs) to build and maintain sandbars. Under the Long-Term Experimental and Management Plan final Environmental Impact Statement (LTEMP EIS; U.S. Department of Interior, 2016), the implementation of HFEs is specifically linked to modeled sand mass balance over specified sediment accounting windows (July 1st to November 30th, and December 1st to June 30th) to allow HFEs to be implemented at times when they will be most effective, and avoid long-term depletion of the amount of sand in the system.

We modeled the potential effects on sediment resources associated with alternatives under consideration for the Interim Guidelines Supplemental Environmental Impact Statement (Interim Guidelines SEIS; Bureau of Reclamation, 2024a) and the Long-Term Experimental and Management Plan Supplemental Environmental Impact Statement (LTEMP SEIS; Bureau of Reclamation, 2024b). We generated predictions for sand mass balance in Marble Canyon using the Wright and others (2010) Sand Routing Model, and predictions for sandbar volume using the Mueller and Grams (2021) sandbar model. The Sand Routing Model was also the basis for determining when HFEs could be implemented, and for what duration. Model results are published and available (Salter and Grams, 2024).

Sand Routing Model Methods and Assumptions

The Wright and others (2010) Sand Routing Model (SRM) is used to calculate sand mass balance for reaches downstream of GCD. The SRM computes sand loads at River Mile (RM) 30, 61, and 87, chosen because these are locations of sediment-monitoring gaging stations (U.S. Geological Survey, 2024). The model divides the Colorado River into three reaches: Upper Marble Canyon (UMC), between the Paria River and RM 30, Lower Marble Canyon (LMC), between RM 30 and RM 61 (just upstream from the Little Colorado River confluence), and Eastern Grand Canyon (EGC), between RM 61 and RM 87 (Figure 3-1). Required inputs are an initial condition (bed grain size distribution in each reach and bed sediment thickness), discharge time series at each gage location, and time series of tributary sediment inputs from the Paria River and Little Colorado River (LCR).

The model computes sediment loads via a shifting rating curve: for a given bed grain size, sediment loads are a power law function of discharge, but a coarser bed results in less sediment transport for the same discharge, and a finer bed results in more sediment transport for a given discharge. HFE implementation is based on Marble Canyon sand mass balance (i.e., the sum of UMC and LMC mass balances), so for our modeling we ignored EGC and did not need to account for LCR sand loads.

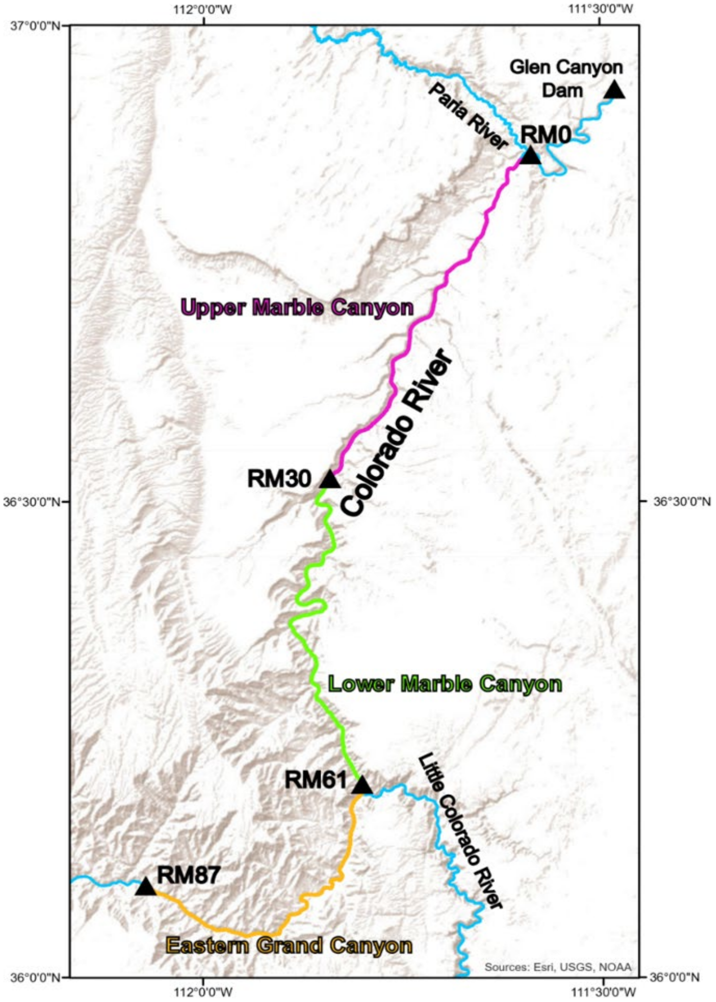


Figure 3-1. Region assessed in sediment modeling. Segments of the mainstem Colorado River are indicated in colors. Key tributaries (Paria River and Little Colorado River) are labeled. Triangles indicate the location of Glen Canyon Dam and referenced gages (U.S. Geological Survey, 2024).

The SRM requires water discharges at each gage location. We used observed discharges at the three gages up until October 2022 (U.S. Geological Survey, 2024) to generate the initial condition (bed, grain size) used in the model, and beyond that we used the projected releases associated with each scenario (Chapter 1).

The timestep for the SRM is 15 minutes; we had hourly hydrographs available for our studies which we linearly interpolated. Typically, when running the Sand Routing Model for future scenarios, the Colorado River Flow and Sediment (CRFS) model (Ecometric Research, Inc., v.1.0.1.0, 2012), which implements the Wiele and Griffin (1998) kinematic wave model, is used to generate the gage discharges, given dam releases. However, running the CRFS model is a time-consuming process as it involves use of a graphical user interface, and running it for all of the scenarios and traces included in the SEIS would be prohibitive. Therefore, we chose to use dam releases at each gage location (U.S. Geological Survey, 2024) , rather than calculating the hydrograph at each gage location. This simplification means that attenuation of discharge waves as they travel downstream is not accounted for in the SRM results. We tested this simplification by comparing SRM results using Lees Ferry discharges at each gage site vs. actual gage discharges at each site and found that the error over 1-year is typically less than 5-10% of the mean annual Paria River sediment load. Based on modeling tests for the amount of sand exported for HFEs of different durations, this error would not typically change the duration of the selected HFE, and would at worse result in a shift up or down of one duration tier.

The initial condition for SRM (bed thicknesses and bed grain size distribution) is based on an SRM model run started from September 1, 2002, using sediment inputs and gage discharges downloaded from the U.S. Geological Survey Grand Canyon Monitoring and Research Center (GCMRC) website (U.S. Geological Survey, 2024). Specific details of setting the initial conditions for the modeling runs differ between the Interim Guidelines SEIS modeling and the LTEMP SEIS modeling because the LTEMP SEIS modeling was completed later, when more data were available. The other key input to the SRM is the sand load time series from the Paria River. To account for the potential variability in Paria River sand loads, we ran multiple sediment traces resampled from the 1996-2023 historical sand loads (U.S. Geological Survey, 2024). Specific details differed between our Interim Guidelines SEIS modeling and the LTEMP SEIS modeling , and are described in chapters “Methods for Interim Guidelines SEIS” and “Methods for LTEMP SEIS.”

Sandbar Model Methods and Assumptions

The Mueller and Grams (2021) sandbar model was calibrated to a set of the nine most dynamic sandbars out of the 45 sandbars that are monitored long-term (Grams and others, 2020; Hazel and others, 2022) . The calibration period was 2015-2022.

The calibrated parameters were the initial bar volume, the base eddy exchange coefficient, and the bar erosion rate parameter. Inputs to the model are discharge, suspended sand concentration, and suspended sand median grain size, all at RM 30.

These are obtained from the RM 30-gage for post-hoc modeling of the past (2015-2023), and from SRM for modeling future scenarios. The model output is sandbar volume above the 8000 cubic feet per second (cfs) reference stage.

Given that dam operations often substantially exceed the 8000 cfs reference threshold, the sandbar volumes do not necessarily represent usable sand (e.g., for camping). This caveat is particularly important when considering some traces which result in elevated discharges (i.e., sustained monthly releases at 20,000 cfs or greater). Sandbar fluvial deposition can only occur at and below river stage. Under some scenarios, the model predicts sandbar building above the 8,000 cfs stage associated with these elevated releases, but a significant proportion of the predicted sandbar volume would be unusable. Caution should be used in interpreting results from the sandbar model for these elevated sustained releases because they are not included in the calibration dataset. The sandbar model assumes a constant exponential erosion rate (i.e., erosion rate proportional to sandbar size), which is independent of discharge. It is therefore unable to capture enhanced erosion rates which would likely result from elevated flows.

Hazel and others (2022) analyzed the effect of peak flow magnitude on sandbar deposition and concluded that releases of 34,000 cfs or greater were required to result in significant deposition at reattachment bars and upper-pool deposits and that discharges of 37,000 cfs or greater were required to result in significant deposition at separation and undifferentiated eddy sandbar types. They defined "significant" as an increase in mean sandbar thickness of more than 5 cm.

Additionally, the sandbar model did not include any short-duration high-magnitude discharge fluctuations over the calibration period, which are included in some of the LTEMP SEIS modeling alternatives. Although it is possible that these types of fluctuations could produce some sandbar building, particularly if they occur under sediment-enriched conditions, previous studies have also shown that repeated flow cycles (fluctuations of any magnitude) cause sandbar erosion (Alvarez and Schmeeckle, 2013). Similarly, 1-hr HFEs were implemented in the Interim Guidelines SEIS modeling, but HFEs of such a short duration have never been tested. We did not allow 1-hr HFEs to be triggered for the LTEMP SEIS modeling because at such a short duration they would not provide much sandbar building, but could cause erosion due to the stage fluctuations.

Methods for Interim Guidelines SEIS

We used the Sand Routing Model and additional constraints described below to determine when HFEs would be triggered and when they could be implemented, and we compiled statistics of trigger/implementation probability and timing. Then we used the Sandbar Model to determine how (if) sandbar size differed between alternatives.

We used the projected hourly releases from the Western Area Power Administration (WAPA) hydropower model (GTMax; Veselka and North, 2001) as the starting point for constructing model input hydrographs.

In cases where Lake Powell declined in elevation below powerpool, we assumed that the monthly volume was released as a constant, steady discharge based on the monthly volume in the Colorado River Midterm Modeling System (CRMMS) model output provided by Reclamation (Chapter I; Shuster, 1998; Bureau of Reclamation 2024a).

A sediment-triggered HFE is defined as the longest-duration HFE that can be performed without causing the Marble Canyon sand mass balance to become negative over the course of an HFE. In the LTEMP EIS HFE protocol, this mass balance constraint is applied separately over Fall (July 1 through November 30) and Spring (December 1 through June 30) sediment accounting windows.

We assumed an HFE magnitude of 40,000 cfs. While full capacity releases (45,000 cfs) would be more effective for rebuilding sandbars (Hazel and others. 2022), low reservoir levels are likely to limit the maximum capacity that can be released. We assumed that HFEs could only be implemented within the specified monthly volumes for each alternative; in other words, we did not borrow water from other months. We additionally did not allow the GCD releases to dip below the LTEMP-specified 8000 cfs during the day and 5000 cfs at night, with ramp rates of 4000 cfs/hr up and 2500 cfs/hr down, unless the GTMax hydrograph already did so (in which case the release was not allowed to go any lower). The LTEMP minimums result in a set of minimum releases (Table 3-1).

Table 3-1. Monthly minimum volume in thousand acre-feet (kaf) to accommodate an HFE of the specified duration without causing flows to drop below LTEMP minimums.

Minimum volume (kaf)	No HFE	1-hr HFE	12-hr HFE	24-hr HFE	36-hr HFE	48-hr HFE	60-hr HFE	72-hr HFE	96-hr HFE
1-month	394.21	426.79	456.18	490.09	522.38	556.29	588.58	622.49	688.69

In addition to volume release constraints, it is impossible to run an HFE if the Lake Powell elevation goes below power pool, because turbine capacity decreases significantly and bypass flow capacity is insufficient. We therefore did not allow HFEs to occur if the Lake Powell elevation was below 3490 ft. Finally, we did not include extended-duration HFEs (i.e., HFEs longer than 96 hours in duration).

To account for the potential variability in Paria River sand loads, for the Sand Routing Model we ran each trace with 22 possible traces of Paria River sediment loads, each associated with a 5-year period (1996-2001, 1997-2002, etc.) and then analyzed the results statistically.

The HFE implementation probability plots are based on the full set of 22 Paria River sediment traces, whereas the sandbar model runs are based on a subset of 4 traces: 1999-2003, 2006-2010, 2011-2015, and 2017 to 2021, representing a high, a low, and two medium input scenarios (Figure 3-2).

We initialized our model runs by using observed inputs for a period starting in October 2022 for the Sand Routing Model, and January 2015 for the Sandbar model. For the months of August and September, 2023, we used projected volumes from the 24-month study and a fluctuation pattern based on July 2023 with a scaling factor to match the projected release volume. At the time the models were run in early August 2023, discharge records for RMs 30 and 61, used in the Sand Routing Model, ended in early June/late May of 2023, so we filled the missing data by using the Wiele and Griffin (1998) Flow Routing Model. Similarly, for the Sandbar Model, we used observed data where available, up until June 2023, and then used the Sand Routing Model to provide input data beyond that. We used observed Paria River sand loads through August 10, 2023, assumed zero sediment input for the remainder of August, and then started the historical Paria River traces on September 1, 2023. Due to the large amount of sand export since July 1, 2023, small observed inputs prior to August 10, 2023, and assumption for simplicity of no sediment inputs for the remainder of August, the probability of a sediment trigger in fall 2023 is lower than for fall of subsequent years.

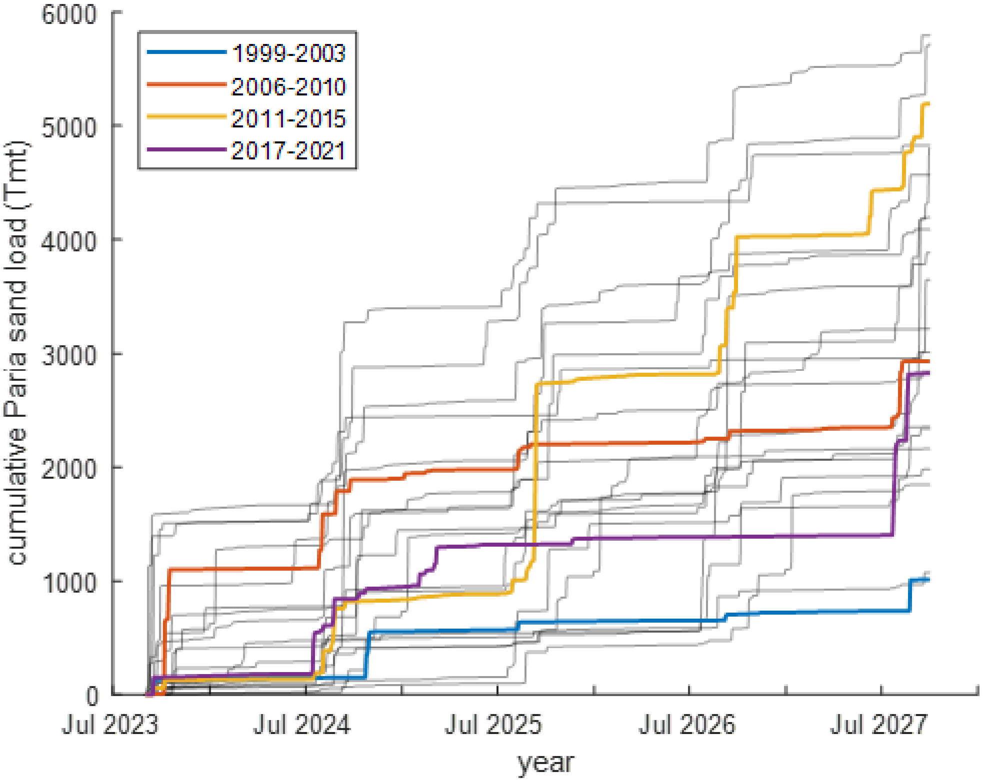


Figure 3-2. Paria River sediment load for 22 traces in thousand metric tons (Tmt) beginning with 1996-2000, used in Sand Routing Model to determine HFE implementation probability. The four labeled traces are the subset used in the Sandbar Model runs (U.S. Geological Survey, 2024).

For the HFE implementation statistics, we ran an initial SRM simulation to determine the cumulative mass balance within each sediment accounting window, and used a heuristic relationship we derived from 1200 simulations with varying bed conditions and durations to determine the sand mass balance that was necessary to trigger an HFE of a particular duration (Figure 3-A36). This allowed us to run all 90 hydrology traces for 22 Paria River sediment traces, which would have been unwieldy if HFE implementation was included explicitly. For the sandbar volume results, we calculated the HFE durations iteratively rather than using the heuristic approach, but only used a subset of four Paria River sediment traces.

Results of Analyzing Interim Guideline SEIS Alternatives

We produced plots of HFE implementation and triggering statistics for each alternative and for all possible implementation windows (i.e., fall and spring of each year in the time series). These plots were based on all 22 Paria River sediment traces and used the mass balance heuristic described in the methods.

Then, we used a subset of four Paria River traces to produce plots of sandbar volume vs. time for each alternative, showing the traces individually as well as their medians and means. As shown in Figures 3-3 through 3-5, there is little to no difference in sediment-triggering of HFEs between the alternatives. However, differences in monthly volumes and reservoir elevations between the alternatives contribute to slight differences in HFE implementation probability when volume and reservoir elevation constraints are considered. In general, the monthly volume constraint affects HFE implementation more than the reservoir elevation constraint for all alternatives; however, in November 2026 there is a slight risk of going below the Lake Powell elevation of 3490 ft under the No Action Alternative (5 out of 90 traces), and smaller risk under Proposed Action Alternative (1 out of 90 traces), which would preclude an HFE of any duration. In general, November monthly releases are slightly lower under the Proposed Action Alternative relative to No Action, and this results in a slight (~5%) reduction in HFE implementation probability for HFE's between 36 and 72 hours in November 2024 and 2025. In November 2026 this difference is partially compensated for by the reservoir elevation constraint. Overall, the difference in HFE implementation probability between the alternatives is small, but can be important in some traces.

We also obtained model predictions of sandbar volume for the two alternatives (Figures 3-6 through 3-8). Although differences between the alternatives can be significant for individual traces, we find that overall, there is little difference in sandbar size between the two alternatives, with almost no median difference in sandbar volume, and a slight mean difference in favor of the No Action Alternative (Figure 3-8); however, the mean difference in final sandbar volume amounts to only 0.3% of the mean sandbar volume.

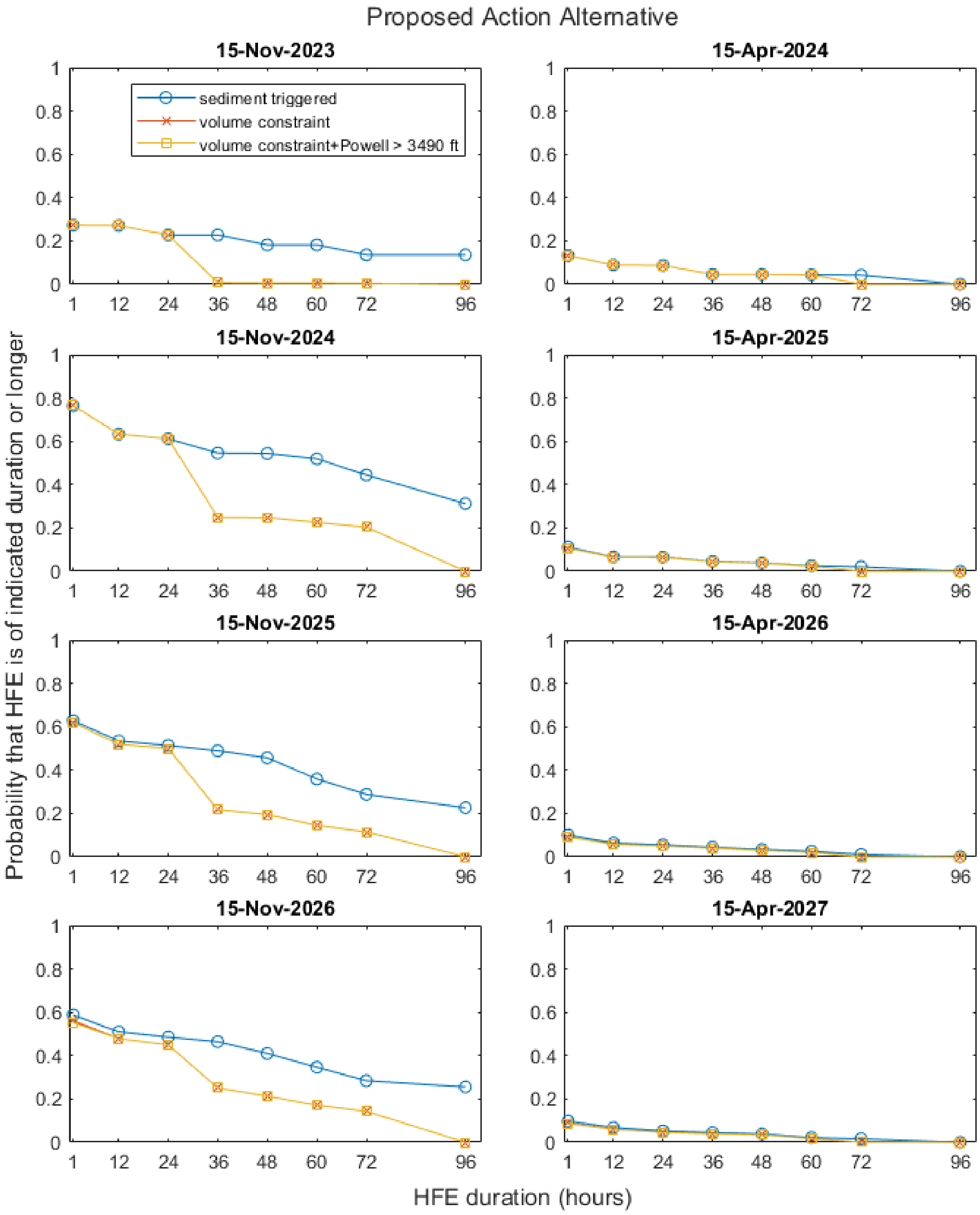


Figure 3-3. Probability of HFE implementation under the Proposed Action Alternative for each potential implementation window, based on 22 Paria River sediment traces x 90 hydrology traces. Note that the "volume constraint" and "volume constraint + Powell >3490 ft" lines overlap considerably (Salter and Grams, 2024).

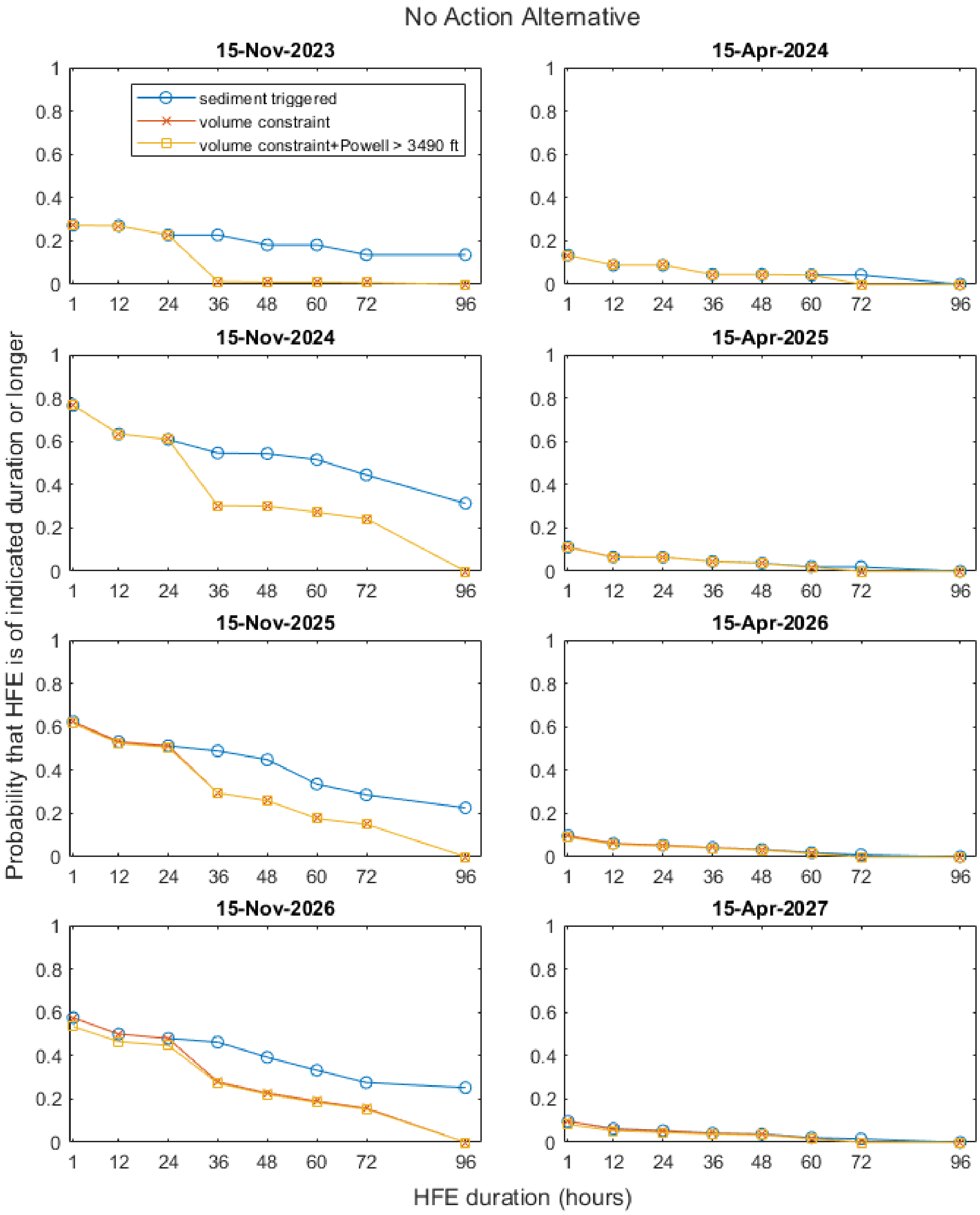


Figure 3-4. Probability of HFE implementation under No Action Alternative for each potential implementation window, based on 22 Paria River sediment traces x 90 hydrology traces (Salter and Grams, 2024).

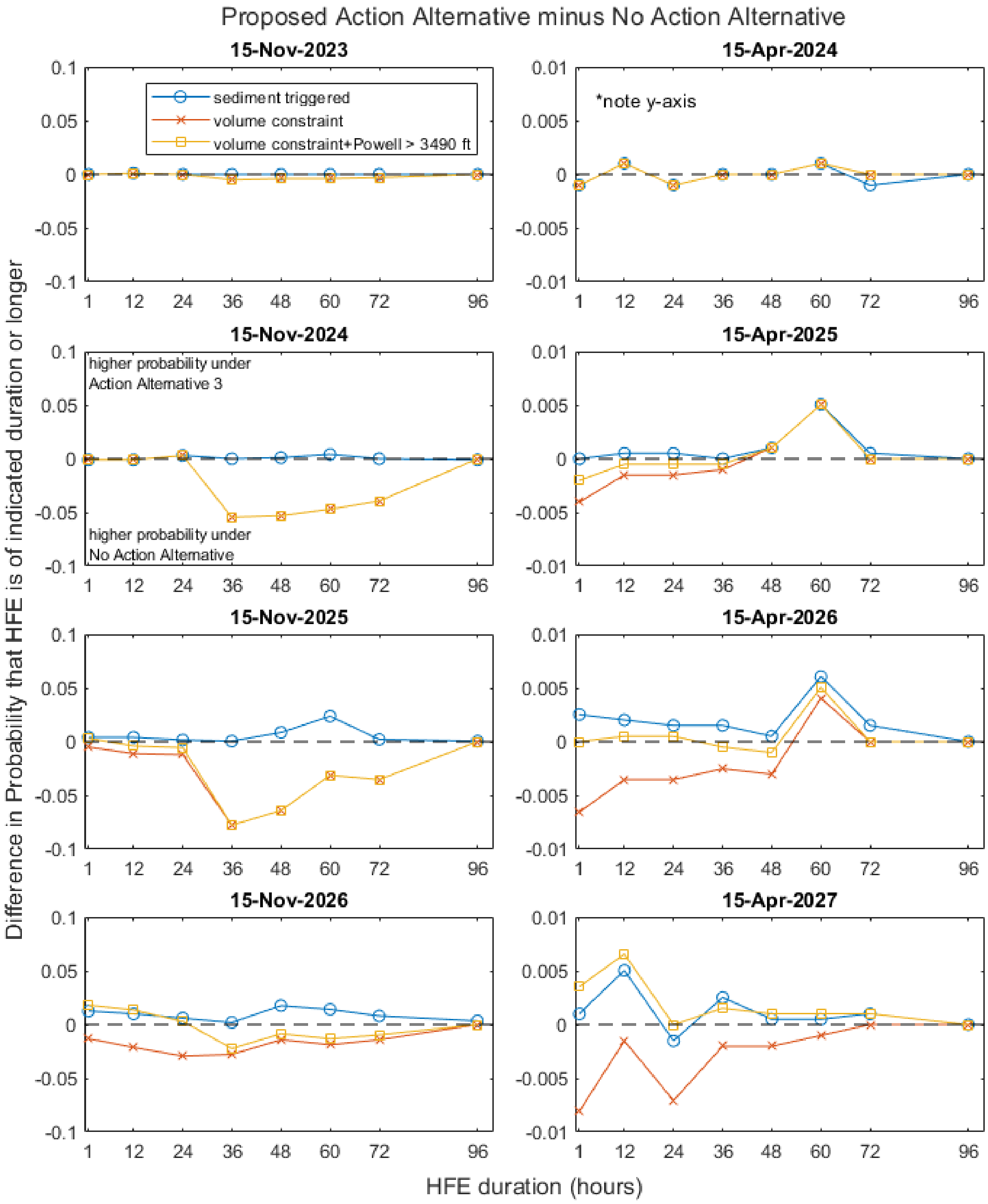


Figure 3-5. Difference in probability of HFE implementation between Proposed Action Alternative and No Action Alternative for each potential implementation window, based on 22 Paria River sediment traces x 90 hydrology traces (Salter and Grams, 2024).

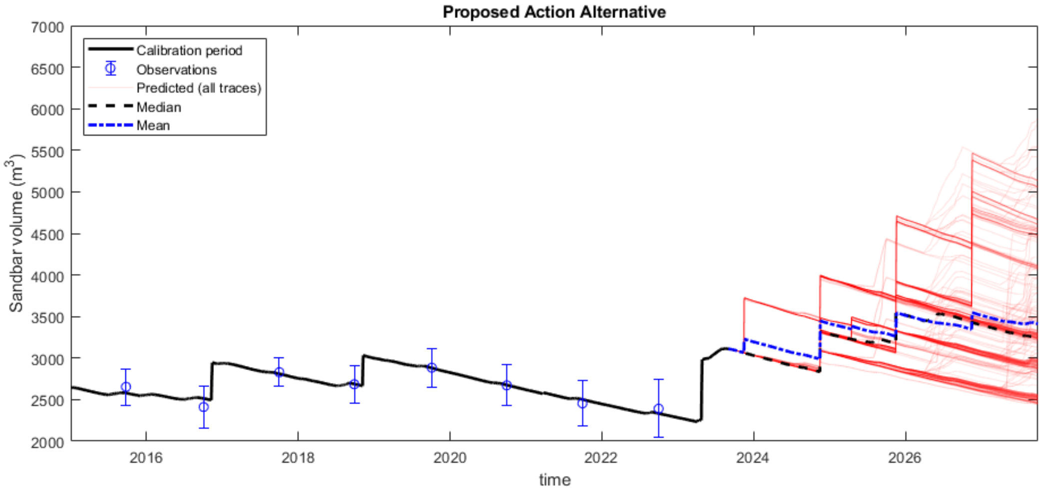


Figure 3-6. Modeled sandbar size under Proposed Action Alternative for all evaluated traces (4 Paria River sediment traces x 90 hydrology traces), with median and mean sandbar sizes superimposed. Lines have transparency, so dark red indicates multiple overlapping lines (Salter and Grams, 2024).

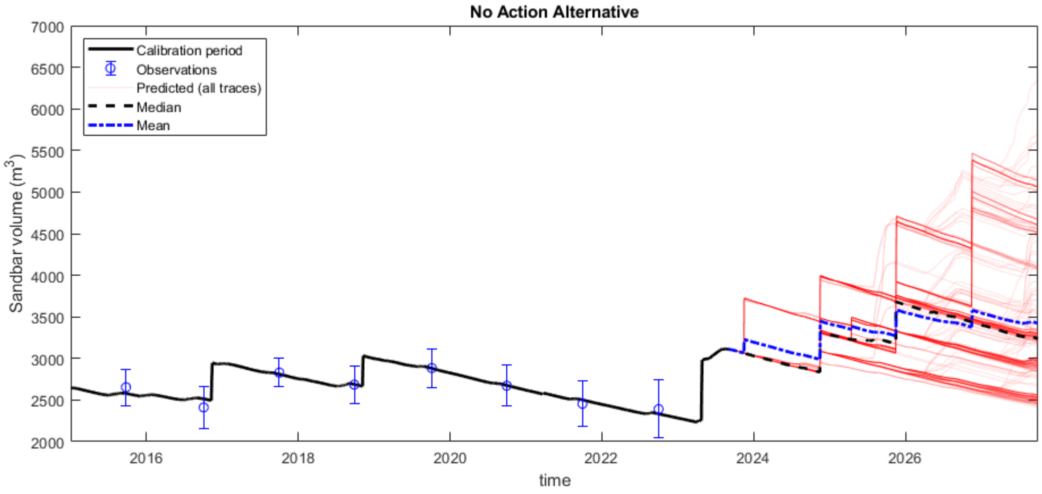


Figure 3-7. Modeled sandbar size under No Action Alternative for all evaluated traces (4 Paria River sediment traces x 90 hydrology traces), with median and mean sandbar sizes superimposed. Lines have transparency, so dark red indicates multiple overlapping lines (Salter and Grams, 2024).

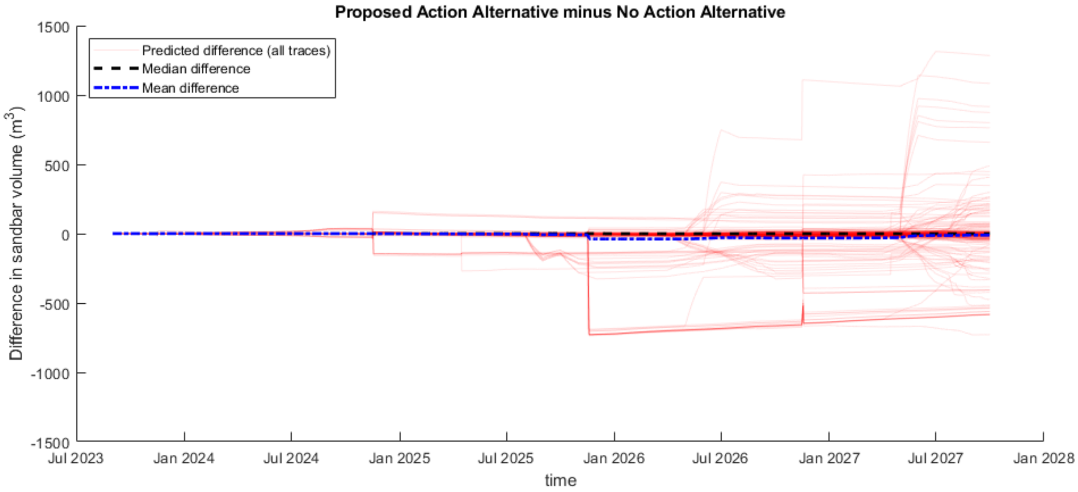


Figure 3-8. Difference in modeled sandbar size between Proposed Action Alternative and the No Action Alternative, with the median difference and mean difference superimposed. Positive values indicate larger sandbars under Proposed Action Alternative relative to No Action; negative values indicate smaller sandbars under Proposed Action Alternative relative to No Action. Lines have transparency, so dark red indicates multiple overlapping lines (Salter and Grams, 2024).

Methods for LTEMP SEIS

As with the previous chapter, model outputs for the figures presented in this chapter are available in Salter and Grams (2024). We used the Wright and others (2010) Sand Routing Model (SRM) to calculate sand mass balance. The HFE magnitude and duration, were selected via iteration according to the sand mass balance. Monthly volumes were distributed if necessary. We used the 100% ensemble streamflow predictions (ESP) hydrology traces from the Interim Guidelines SEIS modeling (Chapter I). For alternatives including flow spikes, we obtained the months that flow spikes would be triggered from the initial run of the smallmouth bass model (Chapter IV this report). For the Non-Bypass Flow Alternative, we assumed that Non-Bypass fluctuations would be triggered in any month for which bypass flows were required under the Cool Mix Alternative with a RM 61 target. Our workflow was to then determine months in which HFEs would be triggered (and their duration and magnitude), if necessary shift monthly volumes to accommodate the HFEs (unlike in our Interim Guidelines SEIS modeling), and also determine the magnitude of flow spikes if they occurred. No modifications to the HFEs occurred after this point in the workflow. For traces in which monthly volumes were modified to accommodate high flow events or flow spikes, we updated Lake Powell elevations during the intervening months based on the same rules implemented in the Colorado River Simulation System (CRSS) Model (Chapter I; Shuster, 1998). This information was passed off for hydropower modeling (Section II of this report) to determine the hourly release patterns with greater realism. We then took those hourly release hydrographs and reran both SRM and the Sandbar Model to obtain our final results.

For each trace of each alternative, we completed an initial simulation with the Sand Routing Model (SRM) to determine the duration and timing of HFEs, as well as their magnitude. The HFE magnitude was based on a penstock capacity vs. Lake Powell elevation curve derived from the CRSS Model, and bypass capacity was based on guidance provided by Reclamation on maximum releases to avoid cavitation risk (written communication from William Stewart and Nick Williams, Bureau of Reclamation, November 14, 2023).

Modeling of HFEs used the combined river outlet works capacity for short duration flows (<72 hours), regardless of the length of an HFE. Actual implementation may involve slightly different magnitudes. For the initial set of modeling, we generated synthetic hydrographs from the monthly release volumes by assuming the maximum discharge fluctuations under LTEMP, with a cap at 25,000 cfs or the max penstock release, whichever is lower. We assumed the daily pattern was 12 hours on a steady daily minimum release, with a 4000 cfs/hr ramp up and 2500 cfs/hr ramp down to a steady daily maximum release.

If, however, the minimum release based on the above was below 8000 cfs, we assumed 12 hours on maximum release, with again 4000 cfs/hr ramp up and 2500 cfs/hr ramp down to a steady daily minimum release; this is to avoid going below the LTEMP EIS minimum daily releases, which must be at minimum 8000 cfs for a full 12 hours.

HFEs were implemented in November and/or April, depending on the alternative, with the possibility of delaying until May or June under alternatives with flow spikes. Under the 1-yr sediment accounting window, decision-makers can choose to implement an HFE in fall or spring depending on the information available at that point. For modeling purposes, we assumed that a spring HFE is preferred to a fall HFE and would be selected if modeling as of November 1st indicates that it would be equal to or one duration tier lower in duration than the fall HFE. We emphasize that this is strictly a modeling assumption, and that the 1-yr accounting window alternatives retain flexibility when choosing between implementation windows.

We additionally tested the 1-yr alternative with a slightly different set of assumptions: in this case, we delayed an HFE to spring if the spring HFE duration was projected to be within two tiers of fall duration, or greater than or equal to 60 hours. For the alternatives that include flow spikes, if a spring HFE had been selected and flow spikes occur in May or June, we compared implementing the HFE on April 15th (default) vs. in place of the first flow spike, using sediment inputs up to April 1st. If the durations were equal or within one duration tier, the HFE was implemented in place of the first flow spike.

We assumed no HFEs would be implemented below a Lake Powell elevation of 3500 ft, as HFE magnitude would be below 37,000 cfs, and it could increase the risk of going below power pool elevation of 3490 ft.

Hazel and others (2022) concluded that discharges of 37,000 cfs or greater were required to result in significant deposition at separation and undifferentiated sandbar types (with a 34,000 cfs threshold for reattachment and upper-pool bar types).

Under the 1-yr window, if an HFE were triggered but not implemented due to this constraint, and there were no other HFE's in the accounting window, a positive sand mass balance is carried over into the next accounting window. When monthly volumes were altered, CRSS equations for Lake Powell were rerun between the first and last modified month to create as accurate as possible elevations, however, for all months after the last modified month CRSS was not rerun. HFE and flow spike magnitudes were based on the original rather than the revised elevation, however, differences are generally small.

The LTEMP EIS does not provide specific details on how monthly volumes are to be shifted to accommodate HFEs, but assumptions are necessary for our modeling. If HFE or flow spike implementation plus base releases of 16 thousand acre-feet (kaf)/day result in a monthly volume higher than the initially-specified monthly release volume, volume was borrowed from other months and added to the implementation month.

For the months being borrowed from, flow was reduced to a minimum of 16 kaf/day. For a fall HFE, if reservoir elevation at the end of the implementation month was 3530' or greater, the order in which volumes were borrowed from other months was: April, March, May, February, December, and January. If the elevation was less than 3530 ft, the order was the same but May is excluded, as borrowing from May to release water sooner could diminish the April end-of-month elevation.

If, after going through all borrowing months, the implementation month still did not have sufficient volume, the adjustment process was repeated, using LTEMP minimum flows of approximately 13.1 kaf/day. If there were still not sufficient volume, the HFE duration was reduced to the next lower tier as a last resort. For an April HFE implementation, the borrowing-month order was April, March, May, June, September, August, then July. For HFEs or flow spikes implemented in May or June, or flow spikes implemented in July, August, or September, the order was the same as above, except the implementation month was borrowed from before any other month.

Each of the 30 hydrology traces was randomly assigned a trace of Paria River sediment inputs derived from the October 1996 to September 2023 record (U.S. Geological Survey, 2024). Assuming that on October 1, 2023 the trace loops back around to October 1996, for the thirty hydrology traces starting in 1991, the Paria River trace starting years are as follows: 1. 1998, 2. 2010, 3. 2022, 4. 2001, 5. 2014, 6. 2000, 7. 2002, 8. 2015, 9. 2008, 10. 1999, 11. 2018, 12. 2003, 13. 2004, 14. 1996, 15. 2012, 16. 2006, 17. 2005, 18. 2013, 19. 2011, 20. 2007, 21. 2019, 22. 1997, 23. 2016, 24. 2020, 25. 2009, 26. 2021, 27. 2017, 28. 1997, 29. 2000,

30. 2019. Hence, differences between traces are due to a combination of the hydrology and the specific trace of sediment inputs. Additionally, for our modeling to determine HFE statistics, we assigned three random Paria River traces to each hydrology trace for a total of 90 traces. This improved the robustness of our statistics.

The initial condition for SRM (bed thicknesses and bed grain size distribution) was based on an SRM model run from September 1, 2002 to October 1, 2023 using sediment inputs and gage discharges (U.S. Geological Survey, 2024).

For our modeling, the possible HFE durations were 12, 24, 36, 48, 60, 72, 96, 144, 192, and 250 hrs. In our report we will refer to these as "duration tiers". We neglected the possibility of 1-hour HFE's, because such a short duration is unlikely to be sufficient for sandbar building, and could result in adverse erosion. Following LTEMP, the 250-hr option was not allowed to occur until a 192 or 144 hr HFE had been run previously, and if an HFE longer than 96 hours were run in fall, no spring HFE's could be run. The HFE with the longest possible duration resulting in a positive sand mass balance for Marble Canyon for the accounting period is the selected HFE. Under 'No Action', the accounting periods run July 1st to November 30thth, and December 1st to June 30th. For the one-year sediment accounting window, the mass balance between July 1st and the termination of the HFE was used when selecting HFE duration, with the possibility of sediment carryover from the previous year(s) if an HFE was triggered but not implemented (e.g., due to low reservoir elevation).

For alternatives that do not include flow spikes, fall HFEs were assumed to be implemented on November 15, and spring HFEs were implemented on April 15th. However, if flow spikes occurred in May or June and a spring HFE had been triggered, the HFE could be delayed until the first month of flow spike implementation, if the duration for the later implementation date was within one duration tier of the earlier date. When selecting HFE duration, Paria River sand inputs up to the 1st of the implementation month were considered, and a 90% multiplier was used on sand inputs to reflect the 'lower bound' estimate. For the one-year accounting window, the initial decision to implement a fall vs. spring HFE was assumed to occur on November 1st based on sediment inputs to that point. If a spring HFE were selected, the duration was revised based on inputs up to the 1st of the implementation month. After the appropriate HFE duration is selected, the SRM is rerun with the full sediment inputs.

After having completed our initial run of modeling to determine HFE timing, magnitude, and duration, our results were passed off to the next step in the workflow as described previously. We reran SRM with the new hourly hydrographs generated by a hydropower optimization model, and the same Pacria River traces as in the previous round of modeling.

Changes to the mass balance were minimal and we did not make any modifications to HFE durations. We then used the SRM output to provide the concentration and suspended sand median grain size, which along with discharge served as inputs for the Mueller and Grams (2021) sandbar model. The sandbar model was recalibrated to the 2015-2023 period, including data from October 2023 (not included in the version used in the Interim Guidelines SEIS modeling, as that modeling took place before that date). We then ran the sandbar model for each trace, initialized using the October 1, 2023 volume computed in the previous step.

In addition to the above, we ran a single trace of the Non-Bypass Alternative through the Wiele and Griffin (1998) model, implemented in the software CRFS. We generated predictions of discharge at various downstream locations in order to assess minimum and maximum flows associated with the alternative. We used the 2002 hydrology trace. We assumed zero tributary inputs or groundwater exchange (losses or gains). Base flow for the LCR is around 200 cfs, but this is not included in the model. Because the hourly discharges produced by the hydropower model represent average discharge for the hour (as opposed to instantaneous discharge at each time), simple linear interpolation of the time series would result in 3-hour minimum and maximum flow durations at the dam. Therefore, instead of linear interpolation, we used stepwise interpolation (i.e., assuming a constant discharge for each hour in the time series.) This results in an unrealistic staircase pattern at the GCD, but has the benefit of preserving the appropriate minimum and maximum flow durations. By the time the discharge wave arrives at Lees Ferry, the staircase artifact is no longer present. After interpolating the hourly time series, we assumed a 0.1 hr timestep for the model run. We verified that results using a 0.25 hr timestep were nearly identical.

Results of Analyzing LTEMP SEIS Alternatives

HFE likelihood and duration statistics

The 1-yr accounting period provides the flexibility to defer a triggered fall HFE to spring provided that the projected sediment mass balance would allow for a spring HFE. Under this alternative, deferring an HFE would be a decision that depends on the specific circumstances of that year. For modeling purposes, we had to make some assumptions about when a fall HFE would be deferred or not, and throughout this analysis we assumed that a fall HFE would be deferred to spring if doing so would result in an equal duration or one duration tier lower. We term this a “weak” spring preference. Additionally, we tested how modifying this assumption affects HFE statistics, by introducing a “strong” spring preference option, under which we assume that an HFE would be delayed to spring if spring HFE duration is projected to be within two duration tiers of fall duration, or greater than or equal to 60 hours.

For flow spike scenarios we assumed the one-year window with “weak” preference for spring. For this chapter only, we used three different initializations of random Paria River traces for the 30 hydro traces, for a total of 90 unique hydro+Paria River traces. This was to ensure that the statistics are robust. The rest of our LTEMP SEIS analysis assumed a weak spring preference, but we included a limited analysis of the strong spring preference assumption to illustrate how results would differ under a different set of assumptions.

Table 3-2. HFE probability and duration statistics for different alternatives and HFE fall to spring deferral assumptions. Note that values are based on all 30 hydrology traces, even though only 6 traces have flow spikes under the River Mile (RM) 15 target scenario, 12 have flow spikes when using a RM 61 target, and 13 have non-bypass fluctuations, meaning that traces that are identical between alternatives/strategies are included in the averaging. Tables 3-A1, 3-A2, and 3-A3 Tables 3-3, 3-4, and 3-5 in the appendix have versions of this table analyzing only the traces which include flow spikes or non-bypass fluctuations.

	No Flow Spikes (weak spring preference)	No Flow Spikes (strong spring preference)	Flow Spikes RM15	Flow Spikes RM61	No Action	Non-bypass Alternative
Fall HFE probability	0.31	0.29	0.31	0.30	0.60	0.30
Spring HFE probability	0.33	0.35	0.32	0.31	0.04	0.32
Fall HFE probability >=60 hr	0.19	0.17	0.19	0.19	0.48	0.19
Spring HFE probability >=60 hr	0.31	0.33	0.31	0.29	0.004	0.31
Probability of at least one HFE in a year	0.60	0.60	0.59	0.56	0.60	0.58
Probability of at least one HFE >=60 hr in a year	0.50	0.49	0.50	0.48	0.48	0.49
Average number of HFE’s per year	0.64	0.64	0.63	0.61	0.64	0.63
Mean fall HFE duration in hours (not counting zeros)	57.2	55.5	55.8	57.8	97.5	56.5
Median fall HFE duration (not counting zeros)	60	60	60	60	96	60
Mean spring HFE duration (not counting zeros)	112	108	110	108	32.7	110
Median spring HFE duration (not counting zeros)	96	96	96	96	24	96
Overall mean HFE duration (not counting zeros)	84.8	84.3	83.2	83.3	93.4	84.3
Overall mean HFE duration (including zeros)	54.3	53.7	52.7	50.6	60.2	52.7

As shown in Table 3-2, for fall HFE probability, unsurprisingly under the one-year window (No Flow Spikes) there are fewer fall HFE's relative to No Action, because some are deferred to spring. Conversely, there are more spring HFE's under the No Action Alternative, with a 33% probability of a spring HFE vs. 4% under No Action. The discrepancy is slightly larger under a "strong" spring preference, as expected. The probability of at least one HFE in a year is 60% under both the 1-yr window and No Action, and the average number of HFE's per year is 0.64 for both, regardless of strong or weak preference for spring HFE's under the 1-yr window. The difference between probability and average number per year is because very rarely it's possible to have two HFEs in one year under either alternative. Therefore, the 1-yr window alternative changes the timing of HFEs, but doesn't actually change the number of HFEs that would occur. Under the 1-yr window, we find shorter fall HFEs but longer spring HFEs. This indicates that long-duration HFEs are more likely to be deferred to spring than shorter ones. The last row shows that the overall mean HFE duration is slightly shorter for the 1-yr window than for the No Action Alternative.

This is consistent with the assumption that decision makers would defer an HFE from fall to spring even if it means a slightly shorter duration. Under the "strong" preference assumption, the mean duration is even shorter than under the "weak" preference, although the difference between "strong" and "weak" is minor relative to the difference between either and No Action. We find that the flow spike alternatives across the board result in similar or slightly lower HFE probabilities and durations relative to the 1-yr window (weak preference). A RM 61 target results in more flow spikes than the RM 15 target, and this results in lower HFE probabilities. However, the effect of target river mile on HFE duration is mixed/minimal, likely due to shorter HFEs being eliminated from the averaging sample when comparing the RM 61 target to RM 15. HFE statistics for the Non-Bypass Alternative are similar to those for the Flow Spike Alternatives. Probability of at least one HFE in a year is 0.58, which is less than the 0.60 under the 1-yr window, and in between the 0.59 and 0.56 found for Flow Spikes Alternatives with a RM 15 and RM 61 target, respectively. Similarly, the probability of at least one HFE greater than 60-hrs in a given year is 0.49, slightly less than the 0.50 or the 1-yr window, and in between the 0.50 and 0.48 found for the Flow Spike Alternatives. Overall mean HFE duration is 84.3 hrs for the Non-Bypass Alternative, which is less than the 84.8 hrs under the 1-yr alternative, but greater than either Flow Spike Alternative (83.2 and 83.3 hrs).

The following plots (Figures 3-9 through 3-11) show the probability of an HFE of at least a certain duration (i.e., the 1-cumulative distribution function). These results are again based on 90 Paria River+hydro traces. We verified that results with 30 traces are similar to results with 90, indicating that the traces are representative.

Each plot contains five lines: No Action, No Flow Spikes (i.e., 1-yr window, change in sediment accounting window with no small mouth bass flows), flow spikes with a target of RM 15, flow spikes with a target of RM 61, and the Non-Bypass Flow Alternative. Cool Mix and Cold Spike Alternatives have identical HFE statistics to "No Flow Spikes", and the alternatives Cool Mix with Flow Spikes and Cold Shock with Flow Spikes have identical HFE statistics for the same target river mile. The main differences are between "No Action" and "No Flow Spikes," with fewer/shorter Fall HFE's and more/longer spring HFE's for the latter. Results are similar between "No Flow Spikes" and the Flow Spike Alternatives, but in some years, flow spikes cause sand export during the fall HFE accounting window in the lead up to HFE implementation, and therefore reduce the final HFE duration. Overall, we find a slight reduction in HFE probabilities for both Flow Spike Alternatives relative to No Flow Spikes. Additionally, we find that HFE probabilities/durations for the Non-Bypass Alternative fall roughly in between the two Flow Spike Alternatives. We note that the triggering under the Non-Bypass Alternative is based on an RM 61 target.

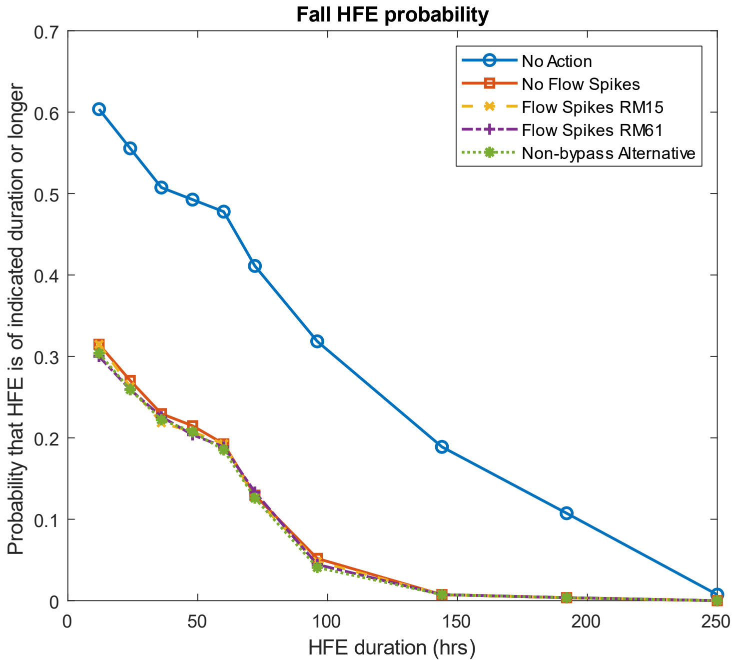


Figure 3-9. Fall HFE probability. Statistics reflect average of 30 traces. Figures 3-A1 through 3-A3 in the appendix have versions of this figure analyzing only the traces which include flow spikes or non-bypass fluctuations (Salter and Grams, 2024).

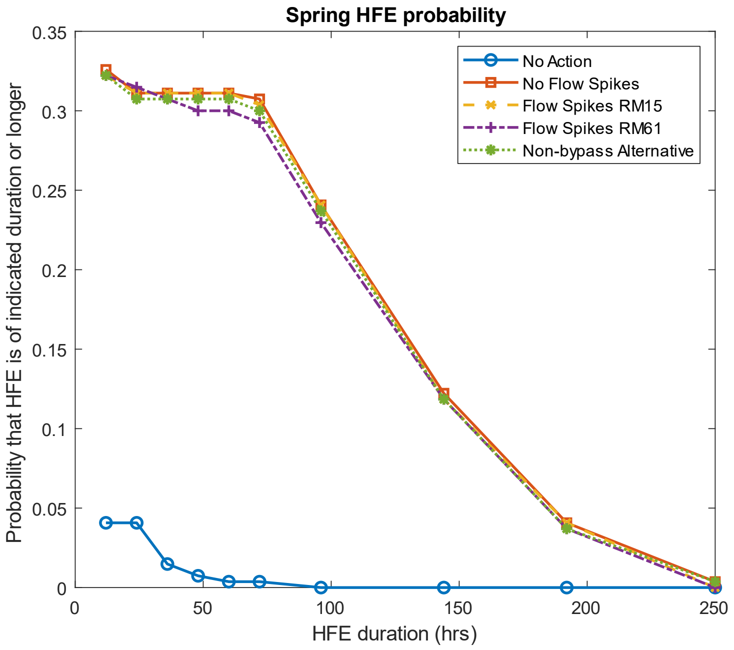


Figure 3-10. Spring HFE probability. Statistics reflect average of 30 traces. Figures 3-A4 through 3-A6 in the appendix have versions of this figure analyzing only the traces which include flow spikes or non-bypass fluctuations (Salter and Grams, 2024.

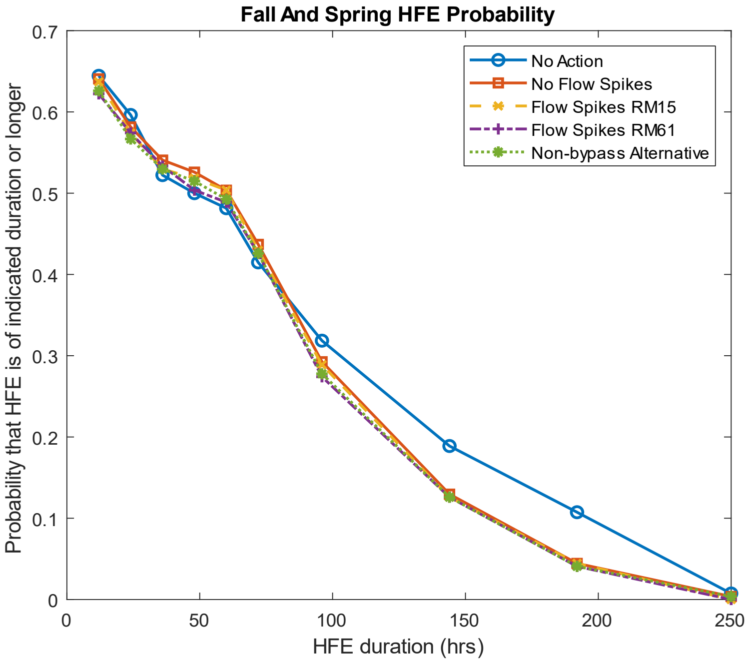


Figure 3-11. Sum of fall and spring HFE probabilities. Statistics reflect average of 30 traces. Figures 3-A7 through 3-A9 in the appendix have versions of this figure analyzing only the traces which include flow spikes or non-bypass fluctuations (Salter and Grams, 2024).

Sand Routing Model Results

We obtained sand mass balance results using the SRM. Among all alternatives, the mean long-term mass balance for Marble Canyon trends negative, but is influenced by a few traces with extreme erosion resulting from high monthly releases due to equalization. Figures 3-A10 through 3-A19 show all traces and their means for each alternative. Figure 3-12 shows just the means, superimposed to allow for comparison. For plotting purposes, the alternatives are grouped into five groups: No Action, “No Flow Spikes” (which includes the 1-yr window alternative and Cool Mix and Cold Shock Alternatives without flow spikes), flow spikes with RM 15 target (both cool mix and cold shock), and flow spikes with RM 61 target (both cool mix and cold shock). Within each group, the mass balances are indistinguishable on the scale of Figure 3-12. Although the hydrographs are not identical within groups, the resulting differences in the sand mass balance are miniscule.

Comparing “No Action” to “No Flow Spikes” we find that the 1-yr window results in a slightly higher mass balance on average. This is the result of slightly shorter average HFE duration under the 1-yr window. Alternatives with flow spikes result in a decrease in sand mass balance. A RM 61 target results in more erosion than RM 15 target, because flow spikes are triggered more frequently. Although the differences in mass balance between the Flow Spike Alternatives and those with the 1-yr window without flow spikes are not dramatic on the scale of Figure 3-12, we note that among individual traces that include flow spikes the mass balance difference can be significant. The difference in the means is reduced because only 6 of 30 traces contain flow spikes for the RM 15 target, 12 of 30 traces contain flow spikes for the RM 61 target, and 13 out of 30 traces contain non-bypass fluctuations under the Non-Bypass Alternative. Additionally, flow spikes that occur in July or later are compensated for by shorter duration HFE’s. We additionally find that the Non-Bypass Alternative results in more sand export relative to the base “No Flow Spikes” Alternatives, and is generally similar to or slightly below the “Flow Spikes RM 61” Alternatives.

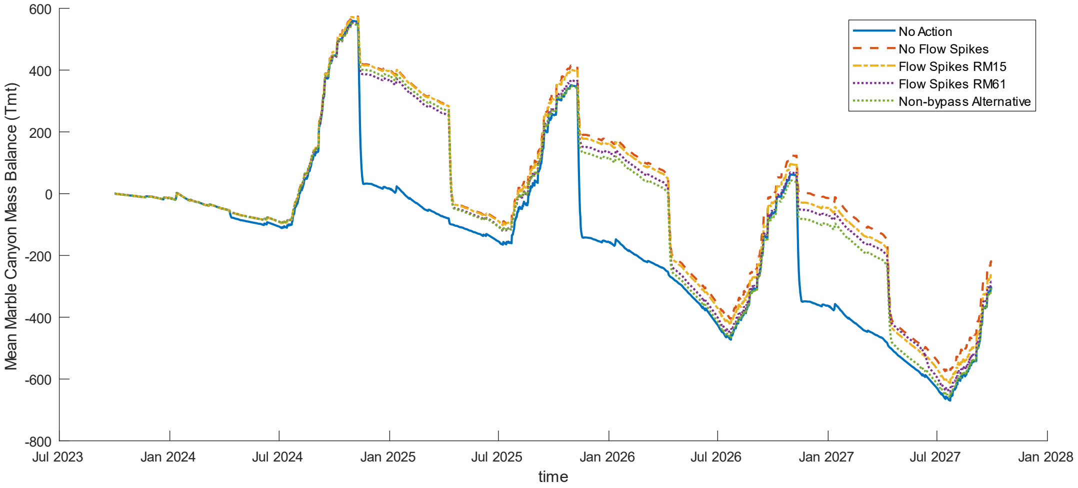


Figure 3-12. Comparison of mean Marble Canyon mass balance Sand Routing Model results for the various Alternatives. Each line represents the mean of 30 traces. Alternatives are grouped into "No Action", "No Flow Spikes", which includes Cold Shock and Cool Mix Alternatives with any target river mile, "Flow Spikes RM 15", which includes both Cool Mix and Cold Shock Alternatives with Flow Spikes and a target of RM 15, "Flow Spikes RM 61", which includes both Cool Mix and Cold Shock Alternatives with Flow Spikes and a target near the Little Colorado River, and "Non-Bypass alternative". Results within each group are non-identical due to subtle differences in release patterns, but would be indistinguishable on the scale of the figure. Figures 3-A20 through 3-A22 in the appendix have versions of this figure analyzing only the traces which include flow spikes or non-bypass fluctuations (Salter and Grams, 2024).

Sandbar Model Results

Figures 3-A23 through 3-A32 show sandbar model results for each alternative and each trace, and Figure 3-13 is a summary plot showing just the mean sandbar volumes for the four groups of alternatives, analogous to Figure 3-12. Figure 3-14 shows an example trace. The primary differences are between the No Action Alternative and the 1-yr accounting window ("No Flow Spikes") Alternatives. The increased probability of spring HFEs is reflected in more frequent but smaller increases in the mean sandbar volume associated with HFEs. The 1-yr window results in smaller sandbars than under No Action, but under either alternative the mean sandbar size grows through time. Smaller sandbar size results primarily from shorter HFE duration, and secondarily from decreased HFE magnitude (April reservoir elevations tend to be lower than in November, hence reduced bypass and penstock capacities), and coarser bed grain size, which reduces suspended sand concentrations and hence sandbar deposition rate.

Flow spike Alternatives are found to produce slightly larger sandbars than the base 1-yr window alternatives. The model predicts modest sandbar growth during flow spikes. We find sandbar volumes for the Non-Bypass Alternative that are similar to the "No Flow Spikes" Alternative, or slightly larger. The sandbar volume predicts slightly smaller volumes for the Non-Bypass Alternative than under the Flow Spike Alternatives, which is because the maximum releases under the "Non-Bypass Alternative" are lower. We note that the Mueller and Grams (2021) model does not include similar flow operations in its calibration dataset (see caveats in the Sandbar Methods and Assumptions chapter), therefore, these results should be interpreted cautiously.

The sandbar model results show that sandbar volume is maximized by implementation of HFEs in fall when sediment retention is greatest and indicates that strategy also results in the greatest potential for long-term increases in sandbar volume. However, if for any reason a Fall HFE is not implemented despite a sediment trigger, as was the case in 2015, 2022, and 2023, the fall-only HFE strategy will result in lower projected sandbar volume than the flexible strategy that allows HFE implementation in either fall or spring.

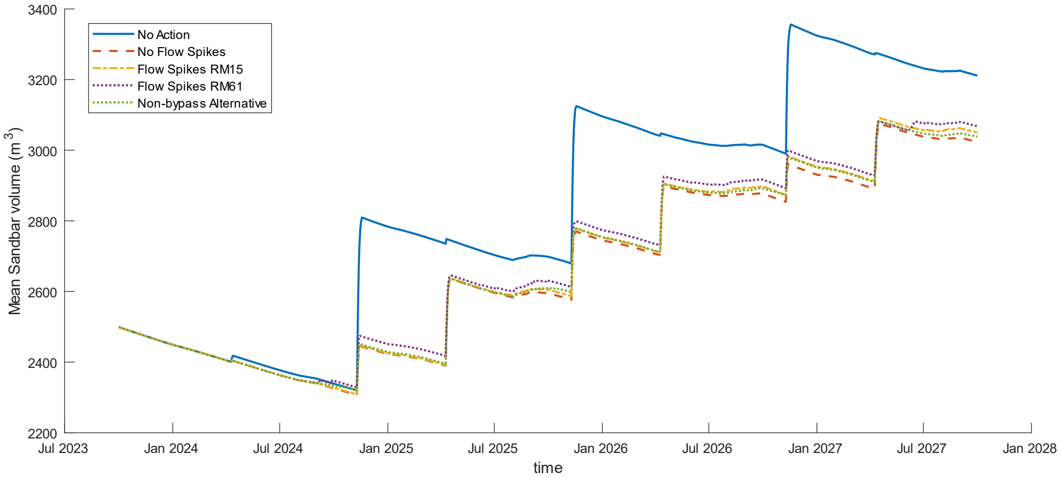


Figure 3-13. Mean sandbar model results for all alternatives. Each line represents the mean of 30 traces. Alternatives are grouped into “No Action”, “No Flow Spikes”, which includes Cold Shock and Cool Mix Alternatives with any target river mile, “Flow Spikes RM 15”, which includes both Cool mix and Cold Shock Alternatives with flow spikes and a target of RM 15, “Flow Spikes RM 61”, which includes both Cool Mix and Cold Shock Alternatives with Flow Spikes and a target near the Little Colorado River, and “Non-Bypass Alternative”. Results within each group are non-identical due to subtle differences in release patterns but would be indistinguishable on the scale of the figure. Under “No Action”, upward steps in fall are much larger than those in spring, since Fall HFE’s are much more likely than Spring HFE’s. For the other three alternatives, fall and spring HFE’s occur with similar probability, resulting in smaller but more frequent upward steps. Note that only 13 of the traces have non-bypass fluctuations, 12 traces have flow spikes with a RM 61 target, and 6 have flow spikes with a RM 15 target. Figures 3-A33 through 3-A35 in the appendix have versions of this figure analyzing only the traces which include flow spikes or non-bypass fluctuations (Salter and Grams, 2024).

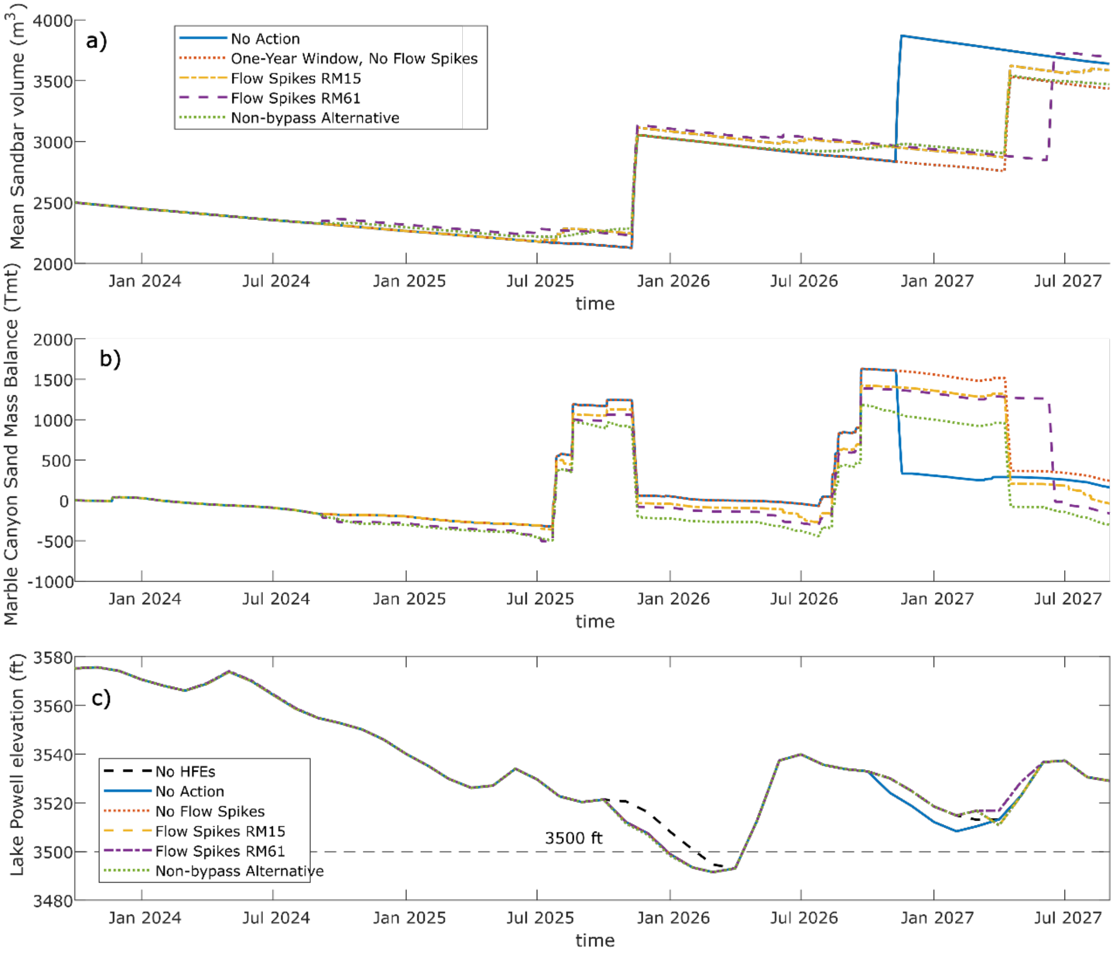


Figure 3-14. Example trace showing a) sandbar volume, b) Marble Canyon sand mass balance, and c) Lake Powell reservoir elevation. Flow spikes in the summers of 2024 and 2025 result in slight sandbar building and sand export from Marble Canyon. All five alternatives trigger HFE's in November of 2025; delay to spring was not possible due to reservoir elevations dropping below the threshold of 3500' (dashed black line in subfigure c). In November 2026, an HFE is run under "No Action", but is delayed to spring under the 1-yr window. Under "Flow Spikes RM 61", the Spring HFE is further delayed to June in order to replace the first flow spike. Although "No Action" results in a slightly larger sandbar than "No Flow Spikes," we note that if the November 2026 were not possible to run due to hypothetical circumstances such as hydrologic conditions, the flexibility under the 1-yr alternative to run a Spring HFE instead would result in much larger sandbars. Reservoir elevations below 3550 ft, as occur in subfigure c for most of the modeled period, have in the past precluded Fall HFEs (Salter and Grams, 2024.

Flow Routing Model Results

We used the Wiele and Griffin (1998) flow routing model to produce results under the Non-Bypass Alternative to determine minimum and maximum flows at different locations in the river. Model results for flows near the Colorado River confluence with the LCR are important for assessing potential effects on humpback chub (*Gila cypha*). As can be seen from Figures 3-15 and 3-16, minimum and maximum flows are at their greatest range at and near GCD, and as the discharge wave travels downstream they attenuate. Therefore, even though minimum flows are 2000 cfs under the Non-Bypass Alternative, by the time the discharge wave reaches the LCR these are substantially higher, close to 5000 cfs. We note that tributary inflows are not included in these results, but their effect could be approximated by adding their discharge to the hydrograph for all points downstream.

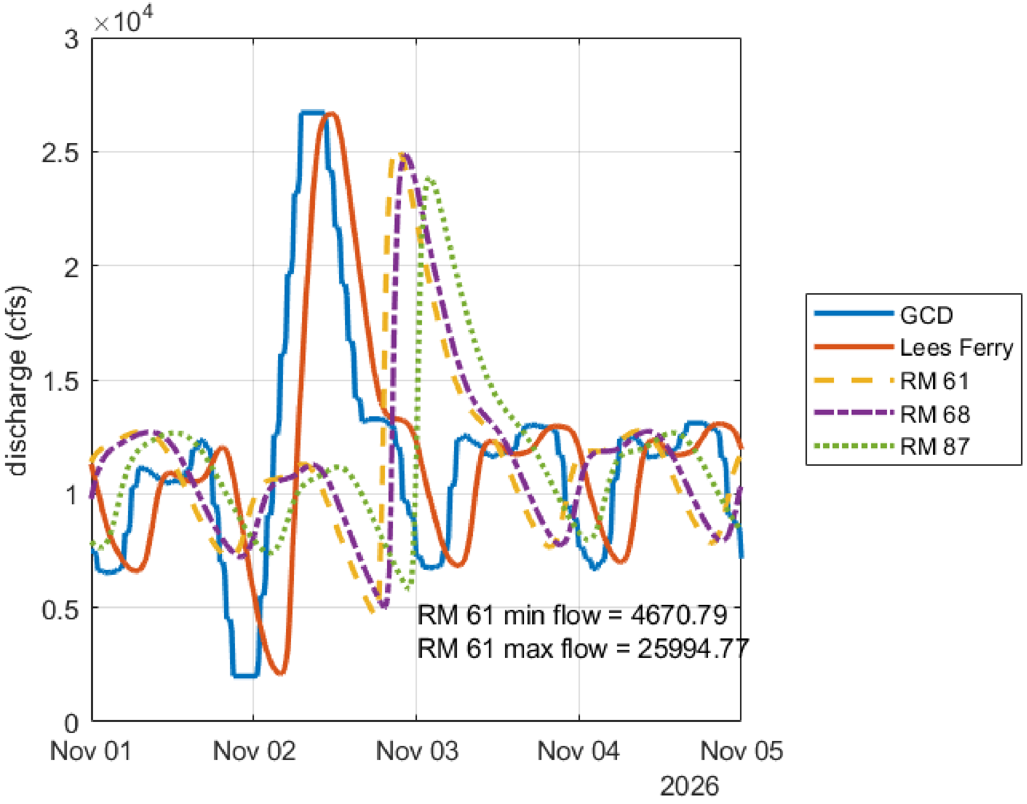


Figure 3-15. Discharge at various locations based on Wiele and Griffin (1998) flow routing model (Salter and Grams, 2024).

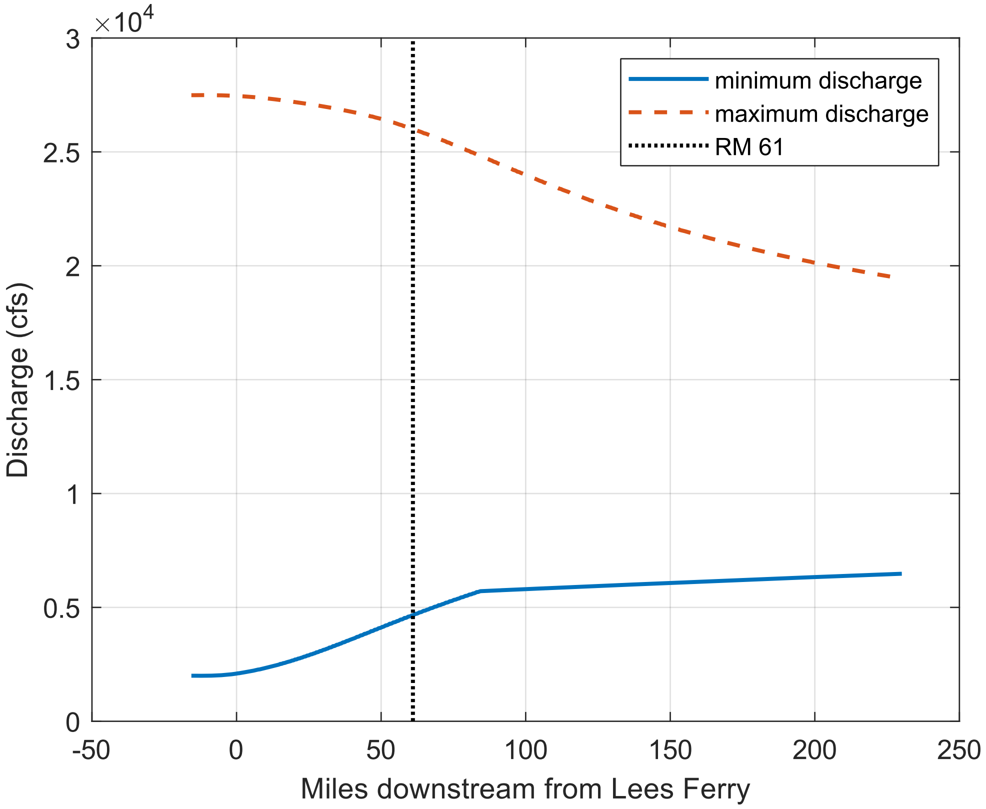
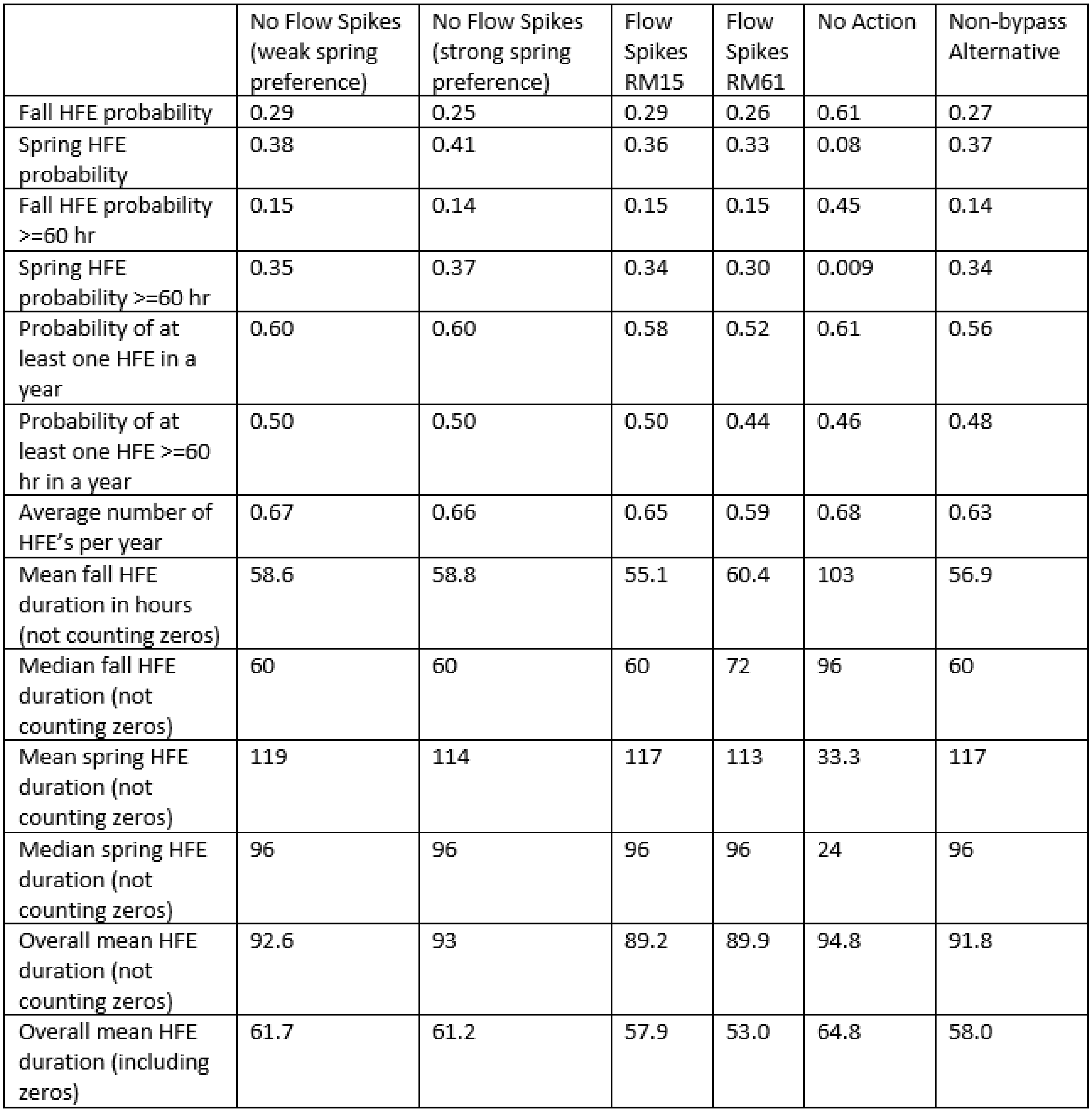


Figure 3-16. Modeled minimum and maximum discharge as a function of distance downstream, based on the time period of May through December 2026 for the Non-Bypass flow Alternative and the 2002 hydrology trace (Salter and Grams, 2024).

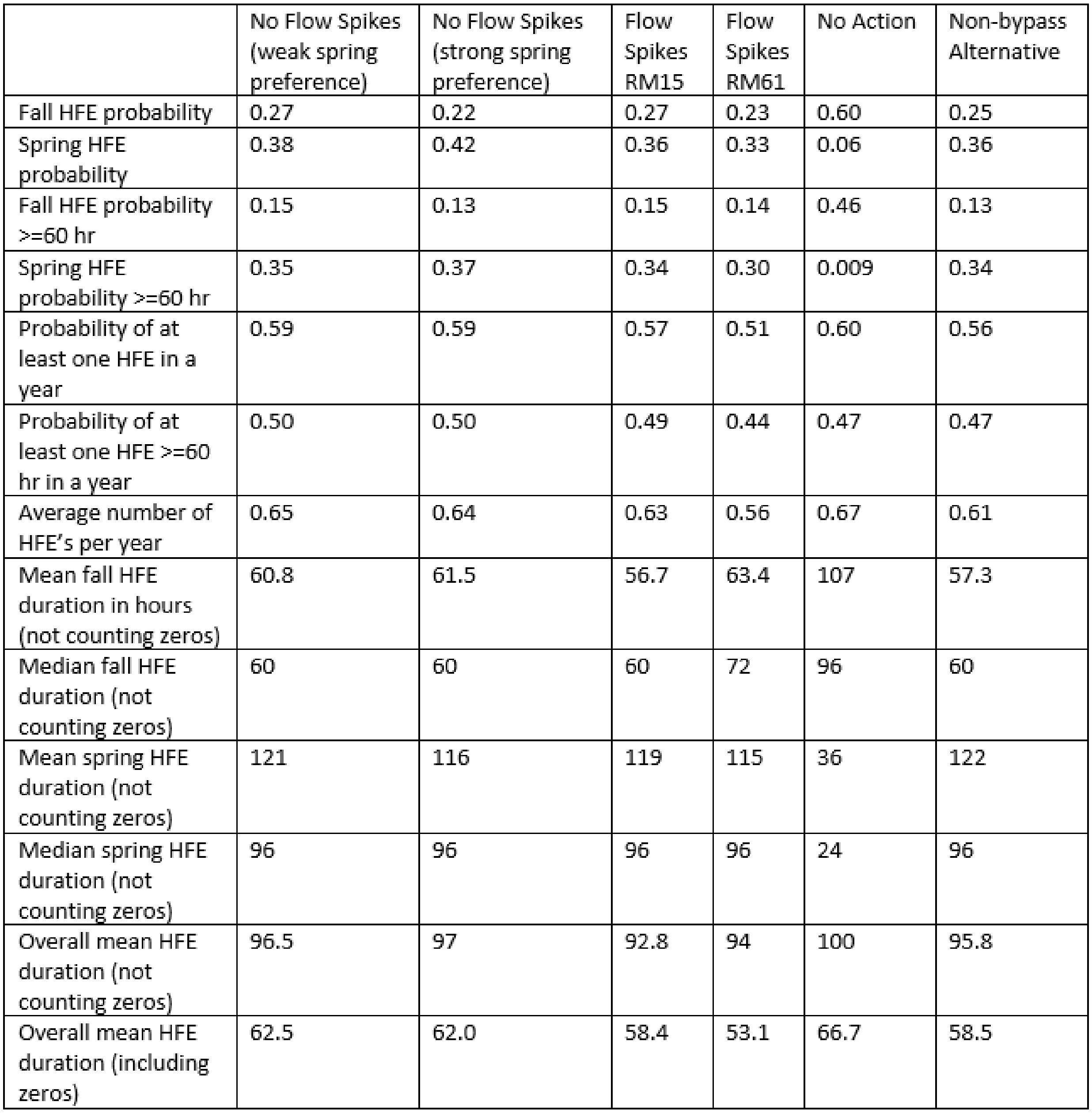
Appendix for Chapter III: Additional Figures for LTEMP SEIS Modeling

Table 3-A1. HFE statistics for traces that under the Non-Bypass Alternative include non-bypass fluctuations (Salter and Grams, 2024).



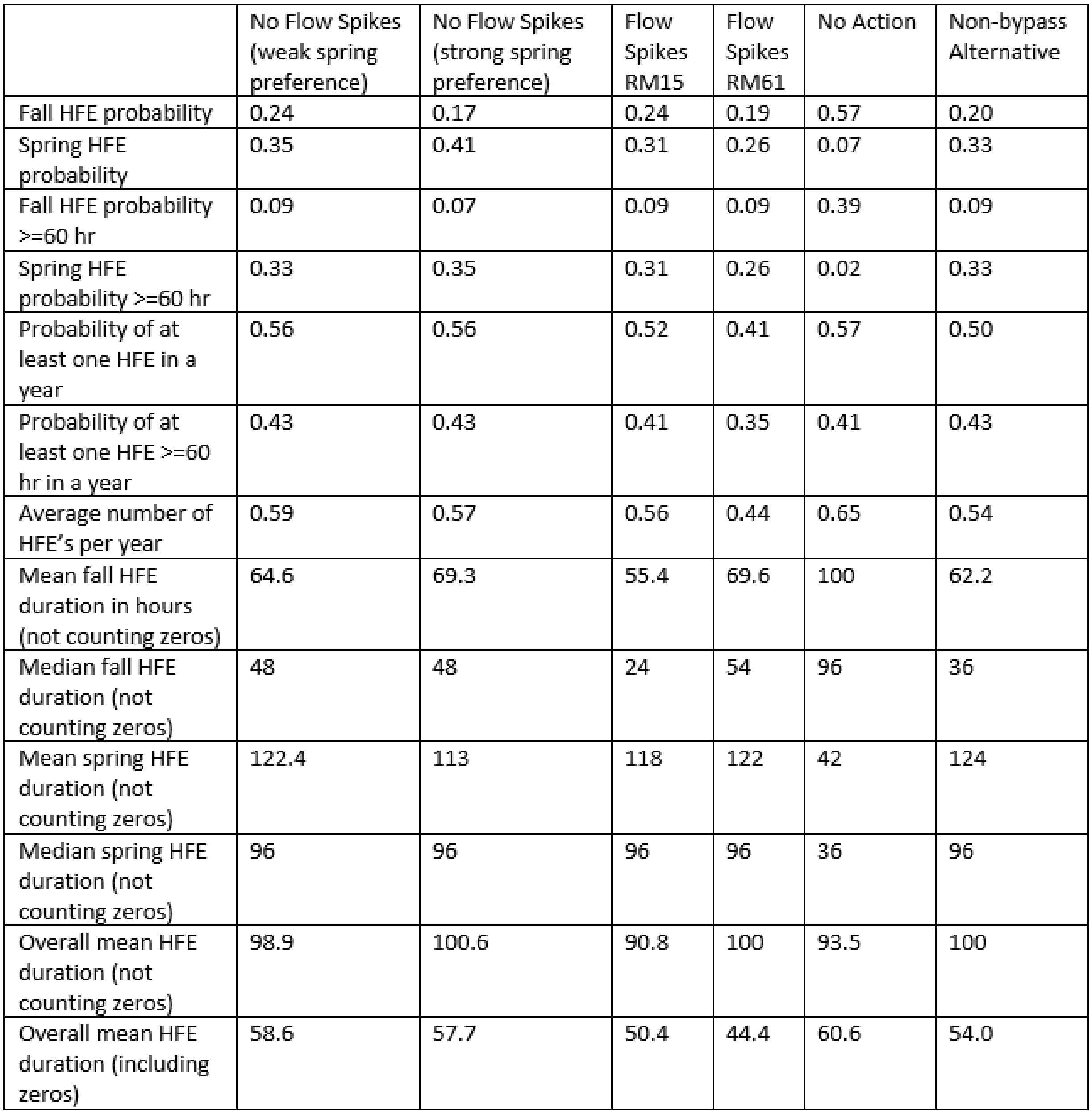
	No Flow Spikes (weak spring preference)	No Flow Spikes (strong spring preference)	Flow Spikes RM15	Flow Spikes RM61	No Action	Non-bypass Alternative
Fall HFE probability	0.29	0.25	0.29	0.26	0.61	0.27
Spring HFE probability	0.38	0.41	0.36	0.33	0.08	0.37
Fall HFE probability >=60 hr	0.15	0.14	0.15	0.15	0.45	0.14
Spring HFE probability >=60 hr	0.35	0.37	0.34	0.30	0.009	0.34
Probability of at least one HFE in a year	0.60	0.60	0.58	0.52	0.61	0.56
Probability of at least one HFE >=60 hr in a year	0.50	0.50	0.50	0.44	0.46	0.48
Average number of HFE's per year	0.67	0.66	0.65	0.59	0.68	0.63
Mean fall HFE duration in hours (not counting zeros)	58.6	58.8	55.1	60.4	103	56.9
Median fall HFE duration (not counting zeros)	60	60	60	72	96	60
Mean spring HFE duration (not counting zeros)	119	114	117	113	33.3	117
Median spring HFE duration (not counting zeros)	96	96	96	96	24	96
Overall mean HFE duration (not counting zeros)	92.6	93	89.2	89.9	94.8	91.8
Overall mean HFE duration (including zeros)	61.7	61.2	57.9	53.0	64.8	58.0

Table 3-A2. HFE statistics for traces that under the Flow Spikes RM 61 scenario include flow spikes (Salter and Grams, 2024).



	No Flow Spikes (weak spring preference)	No Flow Spikes (strong spring preference)	Flow Spikes RM15	Flow Spikes RM61	No Action	Non-bypass Alternative
Fall HFE probability	0.27	0.22	0.27	0.23	0.60	0.25
Spring HFE probability	0.38	0.42	0.36	0.33	0.06	0.36
Fall HFE probability >=60 hr	0.15	0.13	0.15	0.14	0.46	0.13
Spring HFE probability >=60 hr	0.35	0.37	0.34	0.30	0.009	0.34
Probability of at least one HFE in a year	0.59	0.59	0.57	0.51	0.60	0.56
Probability of at least one HFE >=60 hr in a year	0.50	0.50	0.49	0.44	0.47	0.47
Average number of HFE’s per year	0.65	0.64	0.63	0.56	0.67	0.61
Mean fall HFE duration in hours (not counting zeros)	60.8	61.5	56.7	63.4	107	57.3
Median fall HFE duration (not counting zeros)	60	60	60	72	96	60
Mean spring HFE duration (not counting zeros)	121	116	119	115	36	122
Median spring HFE duration (not counting zeros)	96	96	96	96	24	96
Overall mean HFE duration (not counting zeros)	96.5	97	92.8	94	100	95.8
Overall mean HFE duration (including zeros)	62.5	62.0	58.4	53.1	66.7	58.5

Table 3-A3. HFE statistics for traces that under the Flow Spikes RM 15 scenario include flow spikes (Salter and Grams, 2024).



	No Flow Spikes (weak spring preference)	No Flow Spikes (strong spring preference)	Flow Spikes RM15	Flow Spikes RM61	No Action	Non-bypass Alternative
Fall HFE probability	0.24	0.17	0.24	0.19	0.57	0.20
Spring HFE probability	0.35	0.41	0.31	0.26	0.07	0.33
Fall HFE probability >=60 hr	0.09	0.07	0.09	0.09	0.39	0.09
Spring HFE probability >=60 hr	0.33	0.35	0.31	0.26	0.02	0.33
Probability of at least one HFE in a year	0.56	0.56	0.52	0.41	0.57	0.50
Probability of at least one HFE >=60 hr in a year	0.43	0.43	0.41	0.35	0.41	0.43
Average number of HFE's per year	0.59	0.57	0.56	0.44	0.65	0.54
Mean fall HFE duration in hours (not counting zeros)	64.6	69.3	55.4	69.6	100	62.2
Median fall HFE duration (not counting zeros)	48	48	24	54	96	36
Mean spring HFE duration (not counting zeros)	122.4	113	118	122	42	124
Median spring HFE duration (not counting zeros)	96	96	96	96	36	96
Overall mean HFE duration (not counting zeros)	98.9	100.6	90.8	100	93.5	100
Overall mean HFE duration (including zeros)	58.6	57.7	50.4	44.4	60.6	54.0

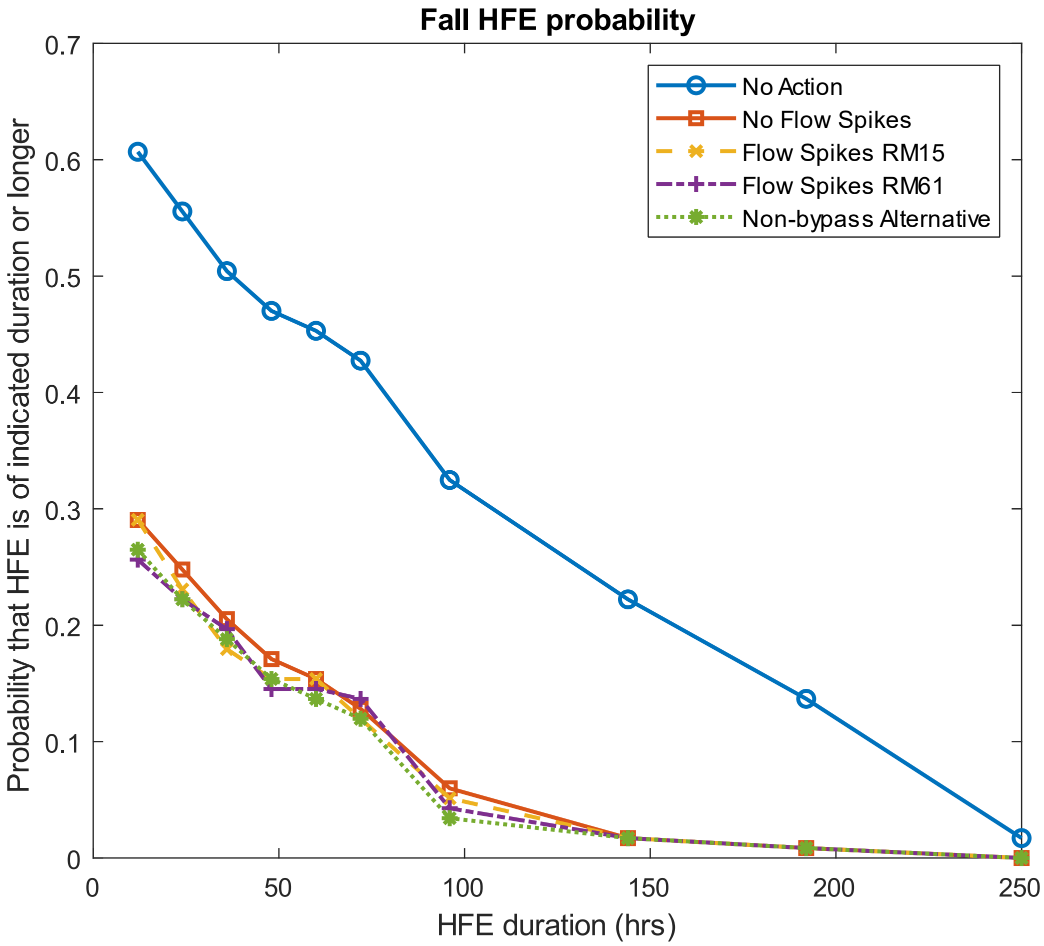


Figure 3-A1. Fall HFE probability for traces that under the Non-Bypass Alternative include non-bypass fluctuations (Salter and Grams, 2024).

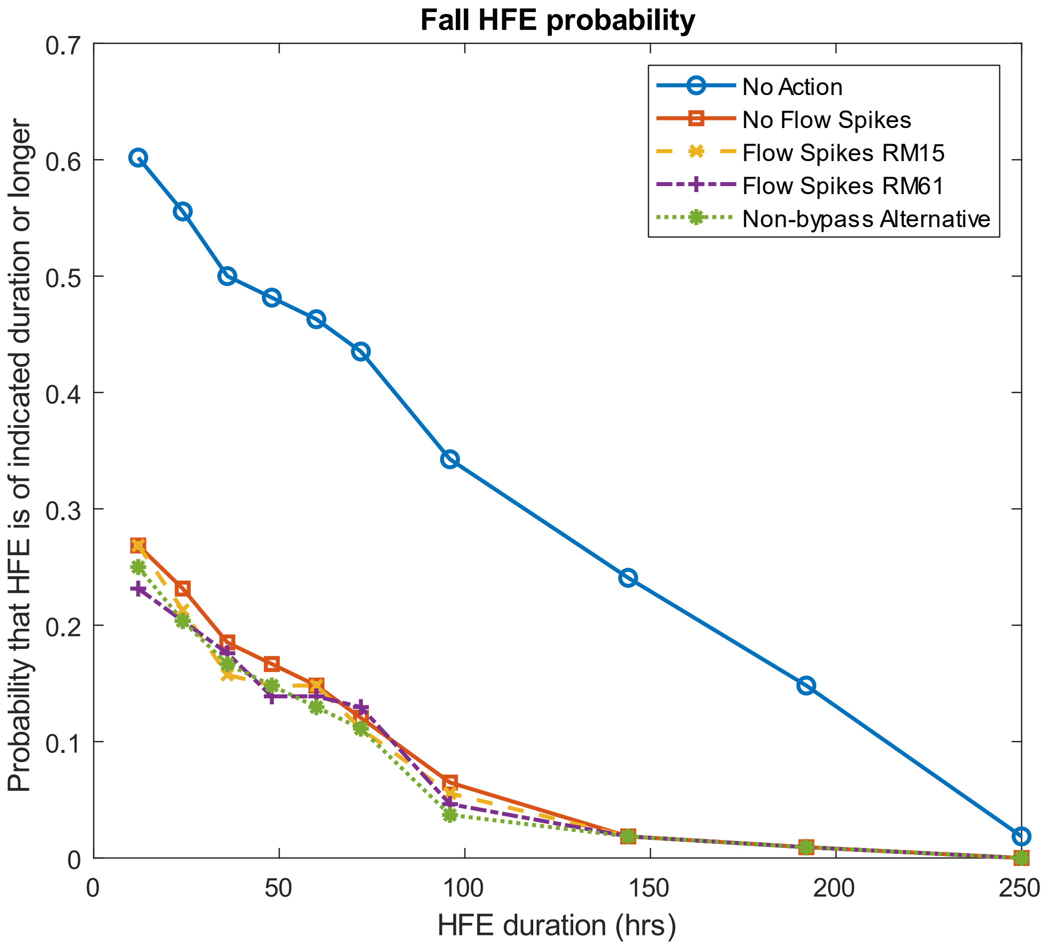


Figure 3-A2. Fall HFE probability for traces that under the Flow Spikes RM 61 scenarios include flow spikes (Salter and Grams, 2024).

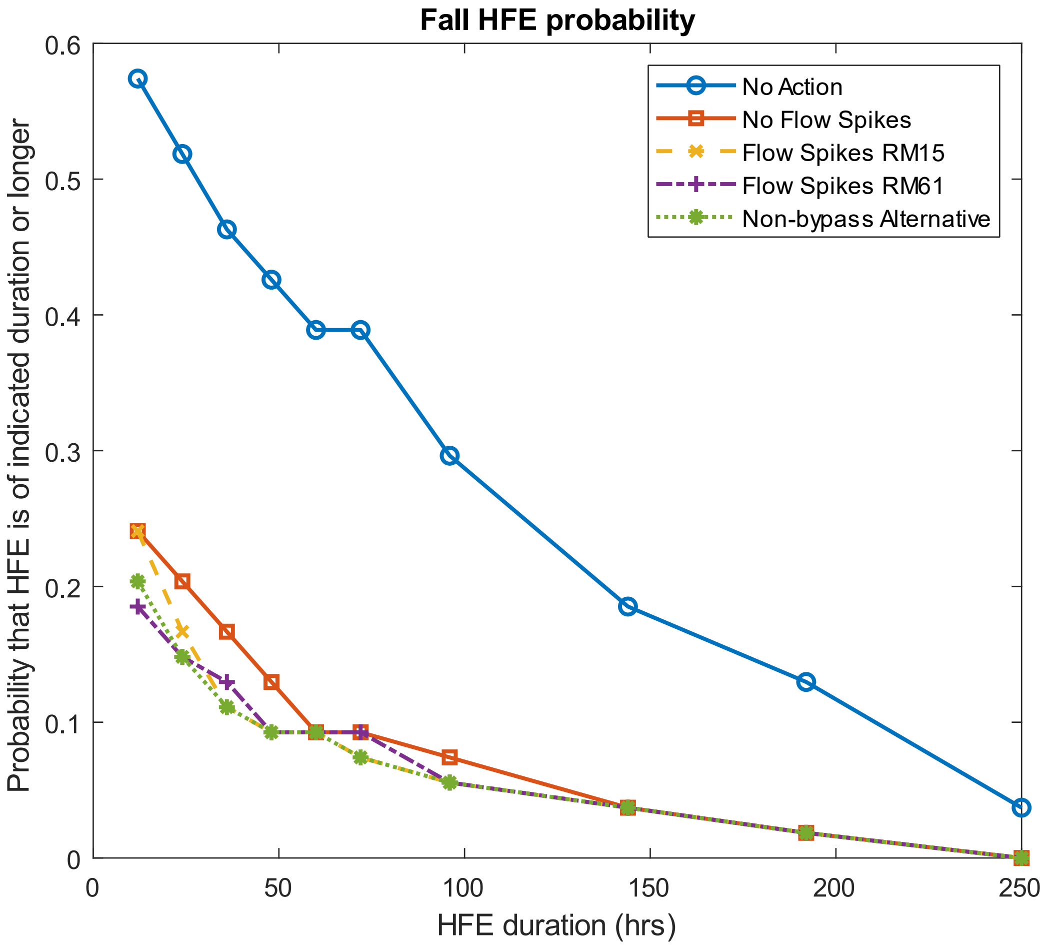


Figure 3-A3. Fall HFE probability for traces that under the Flow Spikes RM 15 scenarios include flow spikes (Salter and Grams, 2024).

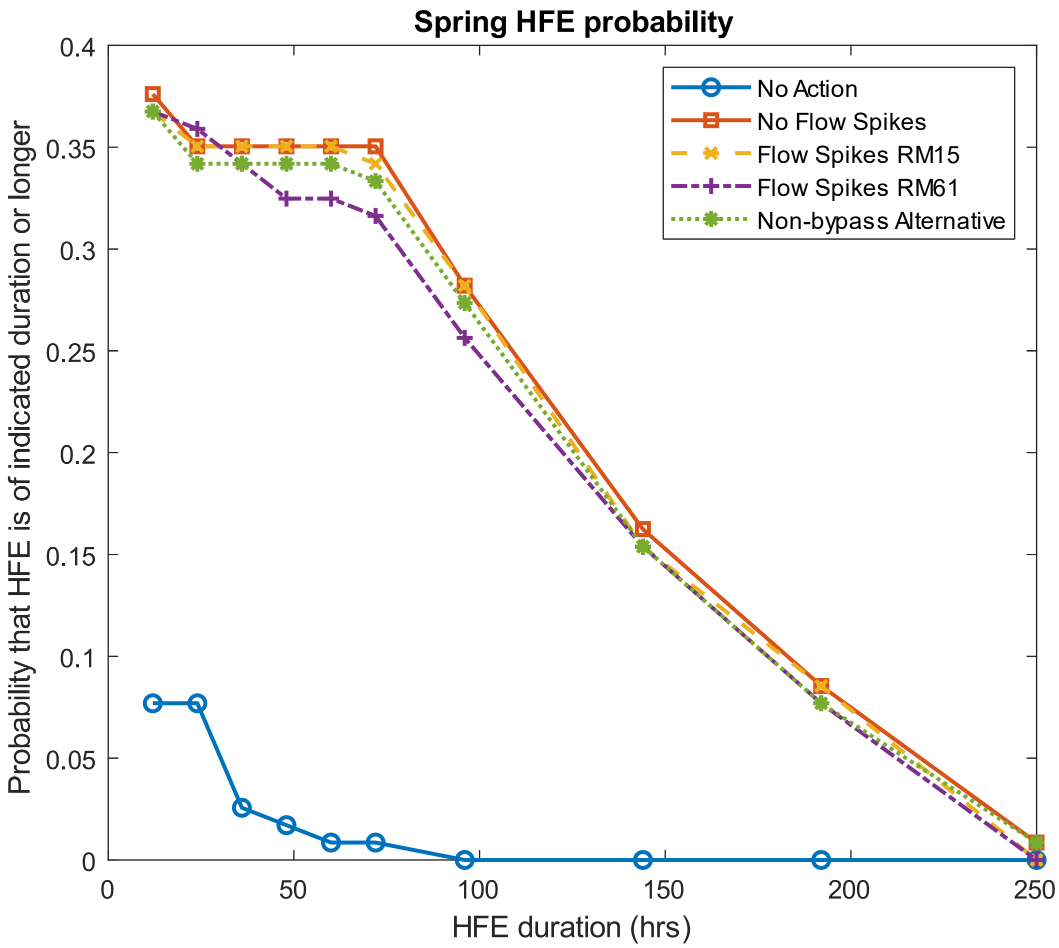


Figure 3-A4. Spring HFE probability for traces that under the Non-Bypass Alternative include non-bypass fluctuations (Salter and Grams, 2024).

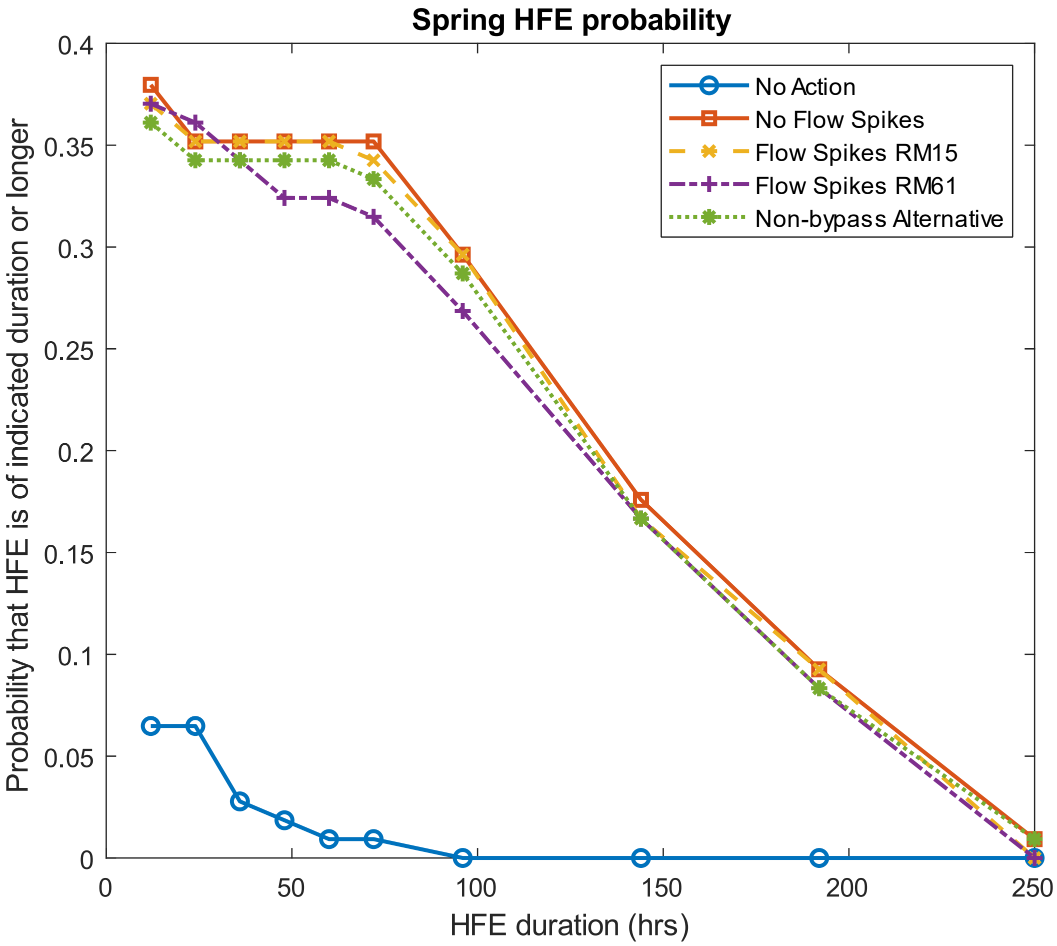


Figure 3-A5. Spring HFE probability for traces that under the Flow Spikes RM 61 scenarios include flow spikes (Salter and Grams, 2024).

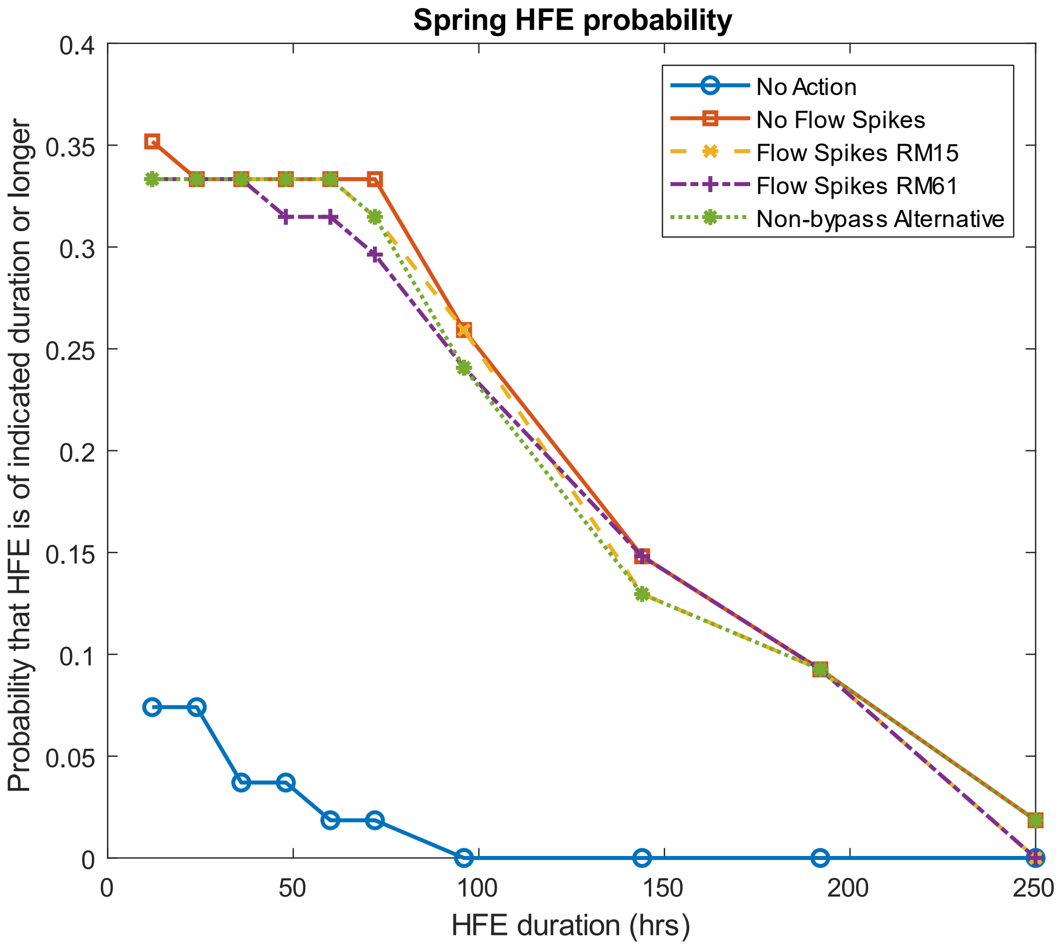


Figure 3-A6. Spring HFE probability for traces that under the Flow Spikes RM 15 scenarios include flow spikes (Salter and Grams, 2024).

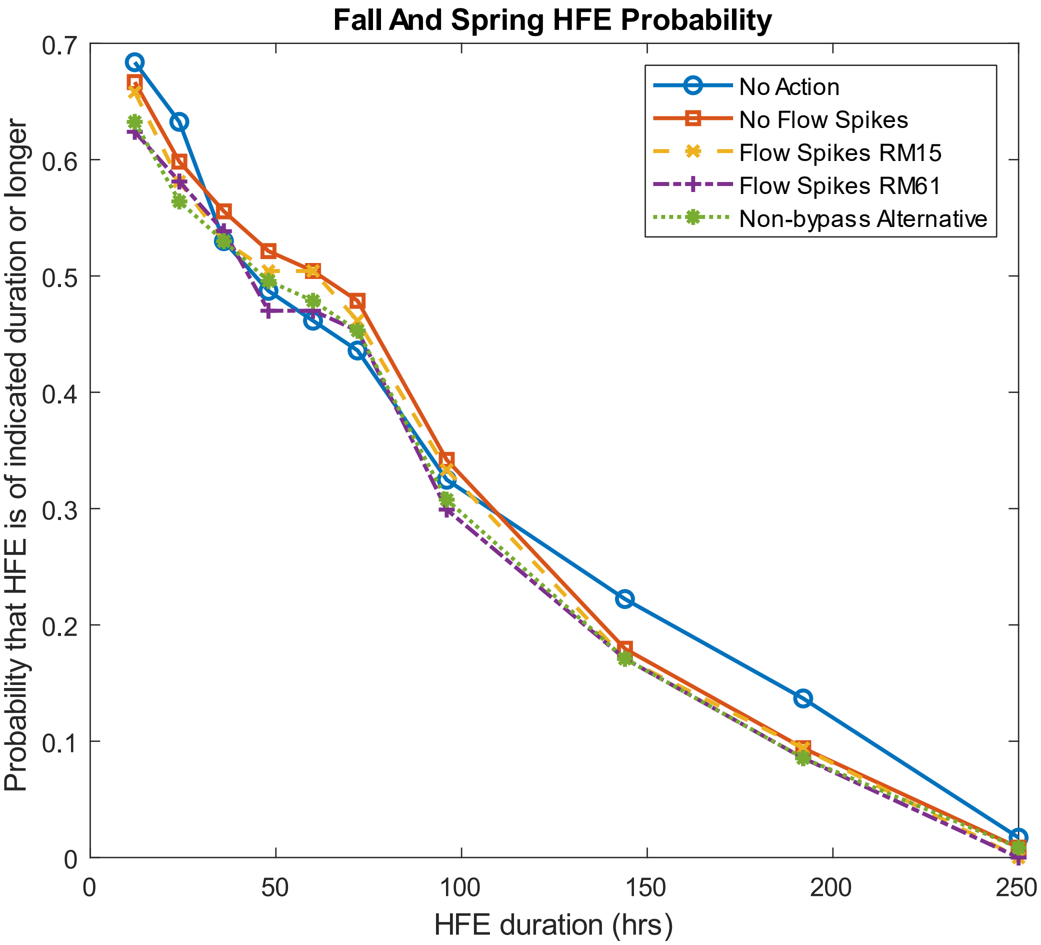


Figure 3-A7. Sum of Fall and Spring HFE probabilities for traces that under the Non-Bypass Alternative include non-bypass fluctuations (Salter and Grams, 2024).

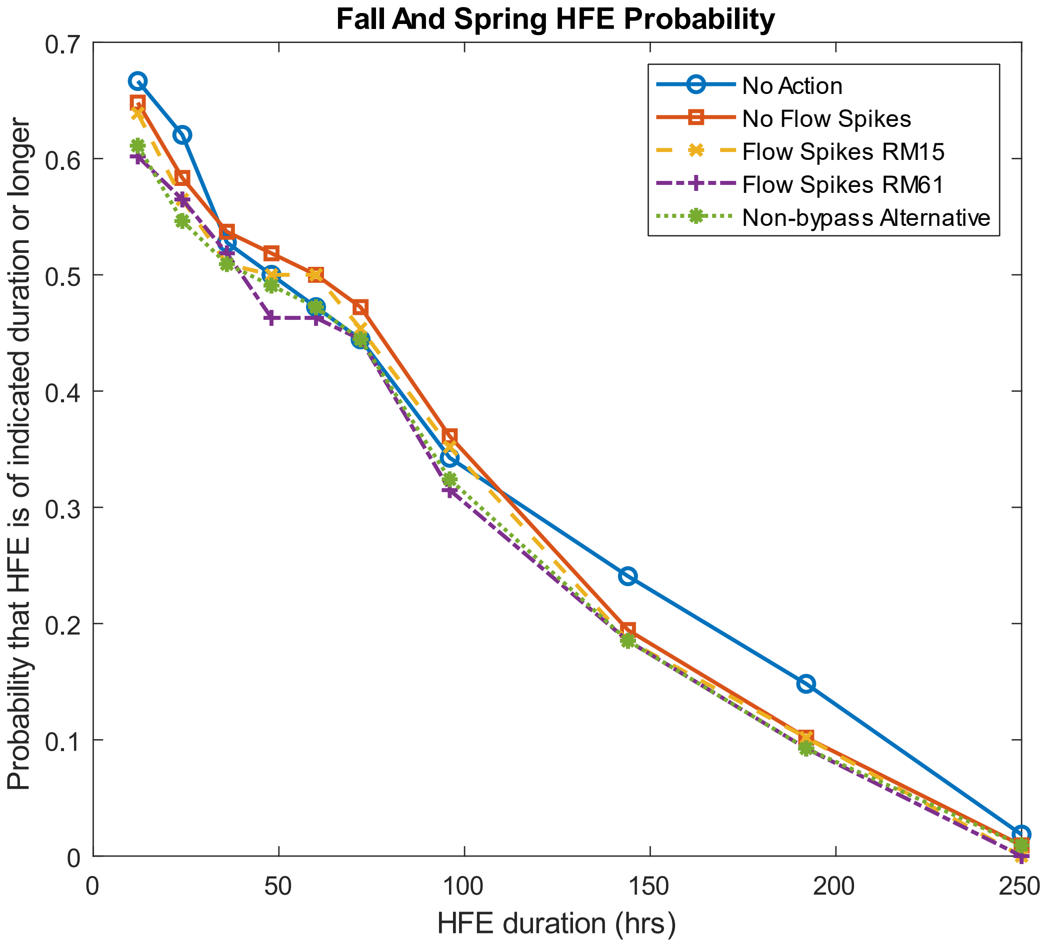


Figure 3-A8. Sum of Fall and Spring HFE probabilities for traces that under the Flow Spikes RM 61 scenarios include flow spikes (Salter and Grams, 2024).

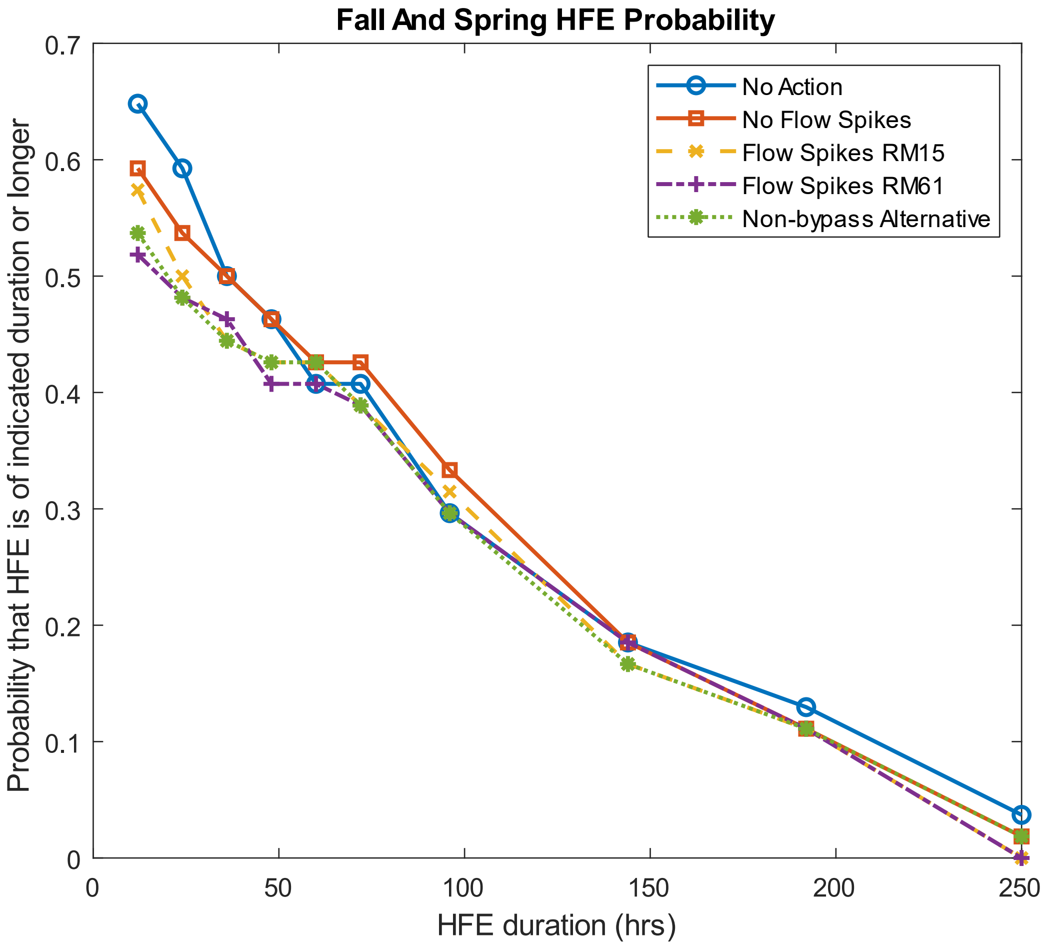


Figure 3-A9. Sum of Fall and Spring HFE probabilities for traces that under the Flow Spikes RM 15 scenarios include flow spikes (Salter and Grams, 2024).

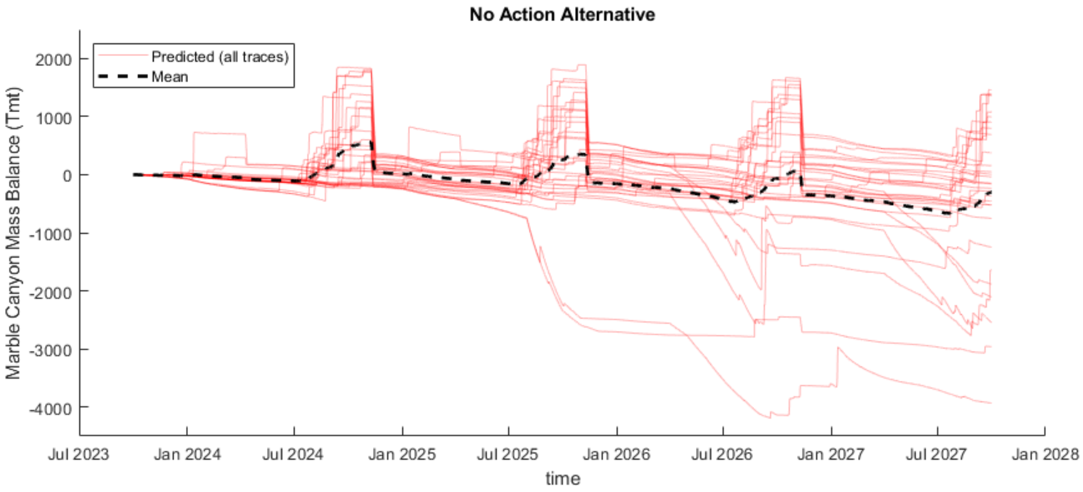


Figure 3-A10. Time series of Marble Canyon mass balance generated by the Sand Routing Model under the "No Action" Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces (Salter and Grams, 2024).

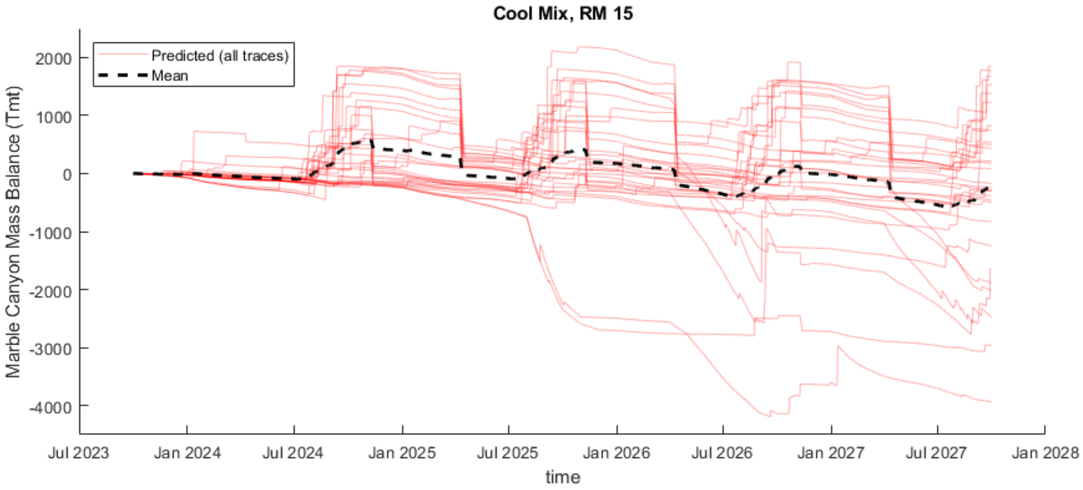


Figure 3-A11. Time series of Marble Canyon mass balance generated by the Sand Routing Model under the "Cool Mix, RM 15" Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces (Salter and Grams, 2024).

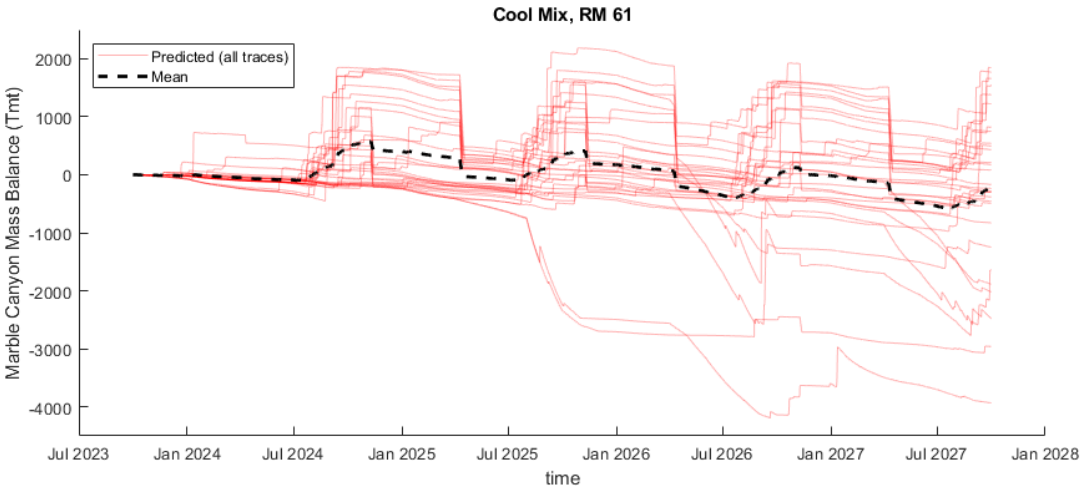


Figure 3-A12. Time series of Marble Canyon mass balance generated by the Sand Routing Model under the “Cool Mix, RM 61” Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces (Salter and Grams, 2024).

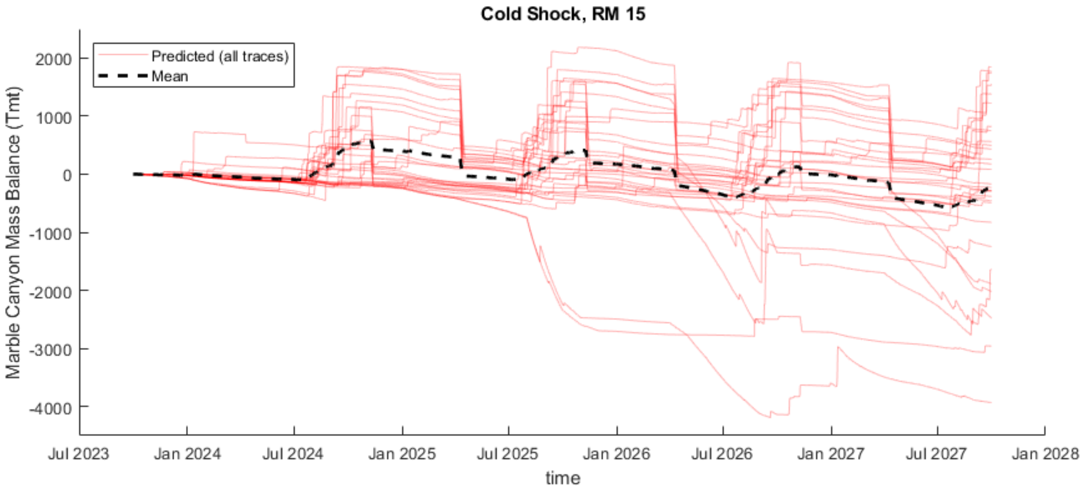


Figure 3-A13. Time series of Marble Canyon mass balance generated by the Sand Routing Model under the “Cold Shock, RM 15” Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces (Salter and Grams, 2024).

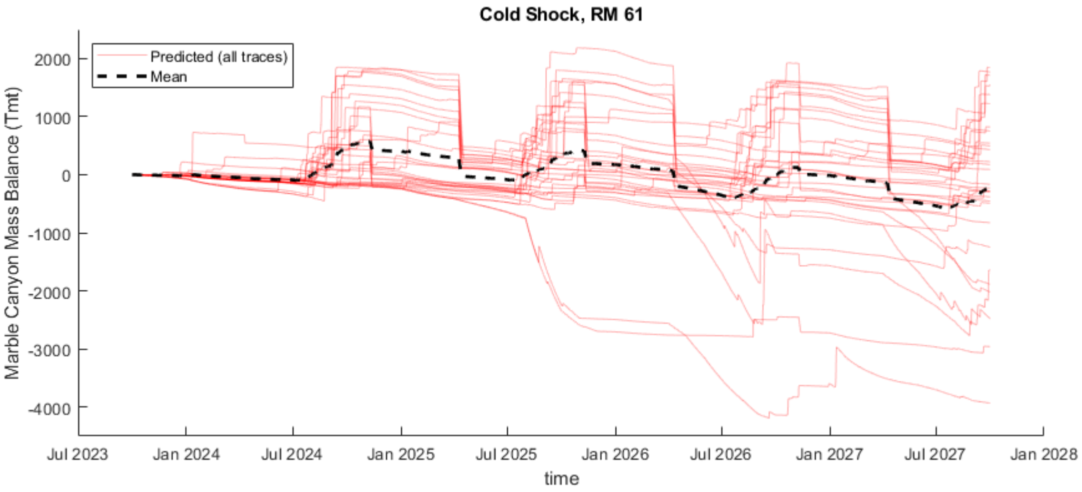


Figure 3-A14. Time series of Marble Canyon mass balance generated by the Sand Routing Model under the "Cold Shock, RM 61" Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces (Salter and Grams, 2024).

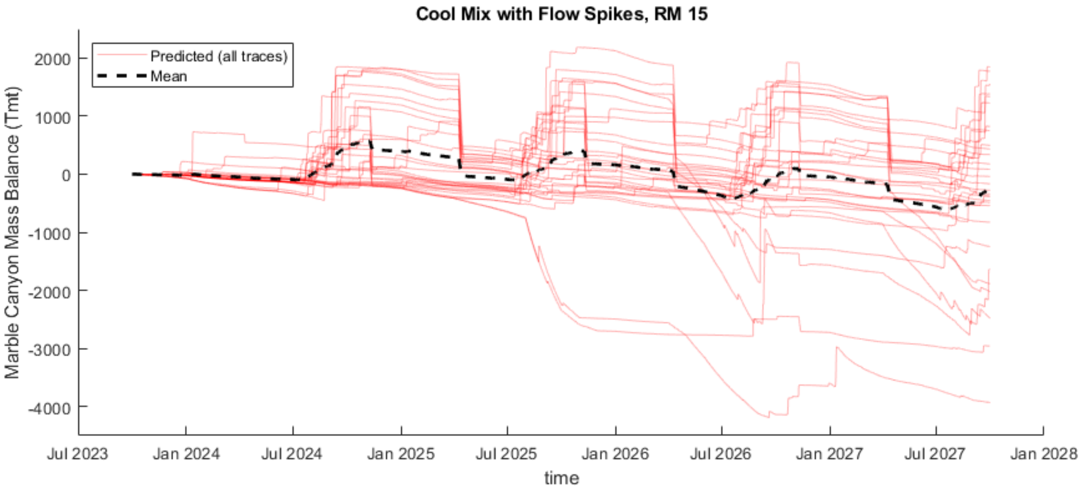


Figure 3-A15. Time series of Marble Canyon mass balance generated by the Sand Routing Model under the "Cool Mix with Flow Spikes, RM 15" Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces (Salter and Grams, 2024).

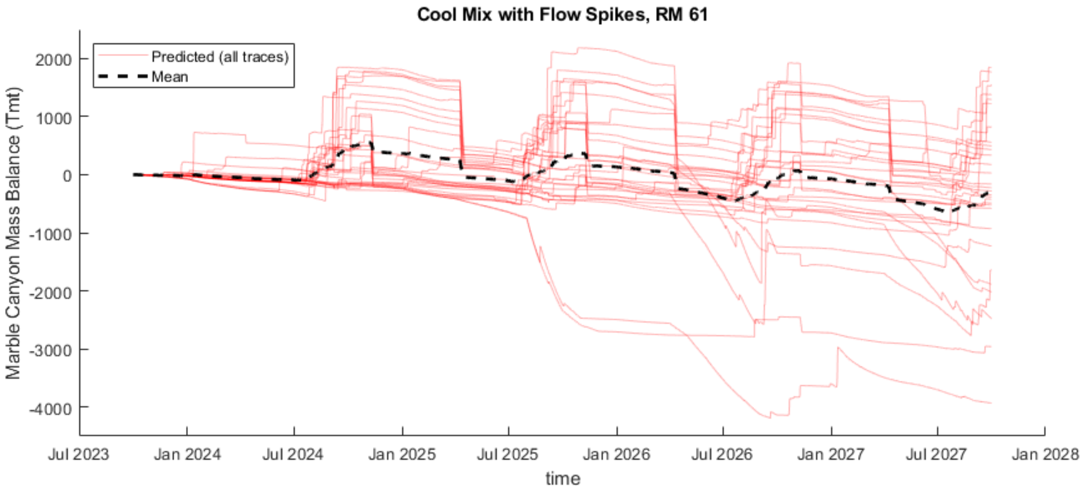


Figure 3-A16. Time series of Marble Canyon mass balance generated by the Sand Routing Model under the "Cool Mix with Flow Spikes, RM 61" Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces (Salter and Grams, 202**4).**

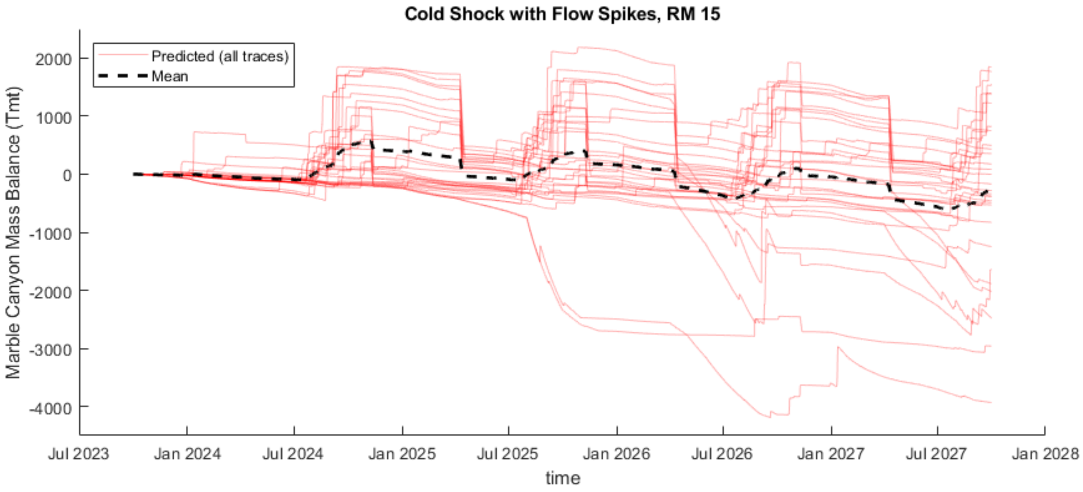


Figure 3-A17. Time series of Marble Canyon mass balance generated by the Sand Routing Model under the "Cold Shock with Flow Spikes, RM 15" Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces (Salter and Grams, 2024).

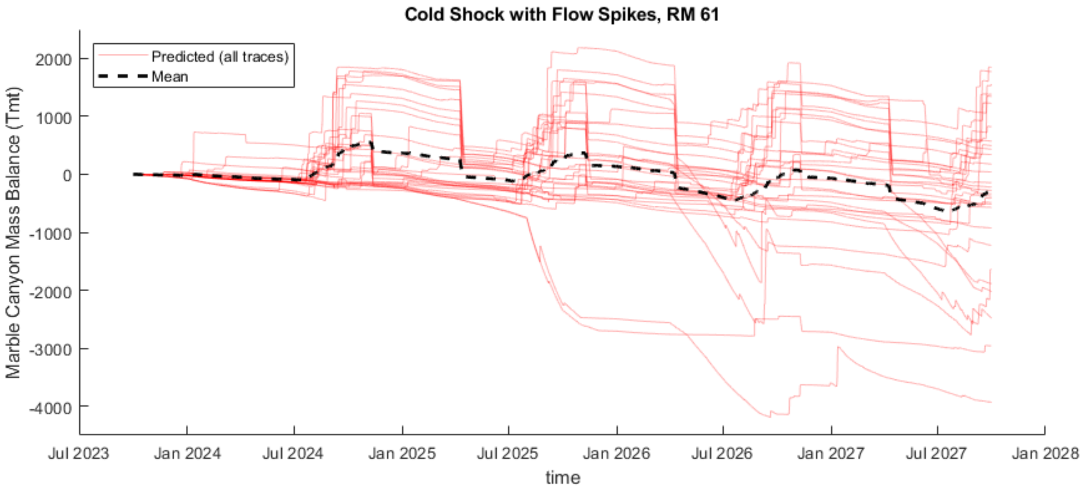


Figure 3-A18. Time series of Marble Canyon mass balance generated by the Sand Routing Model under the "Cold Shock with Flow Spikes, RM 61" Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces (Salter and Grams, 20**24).**

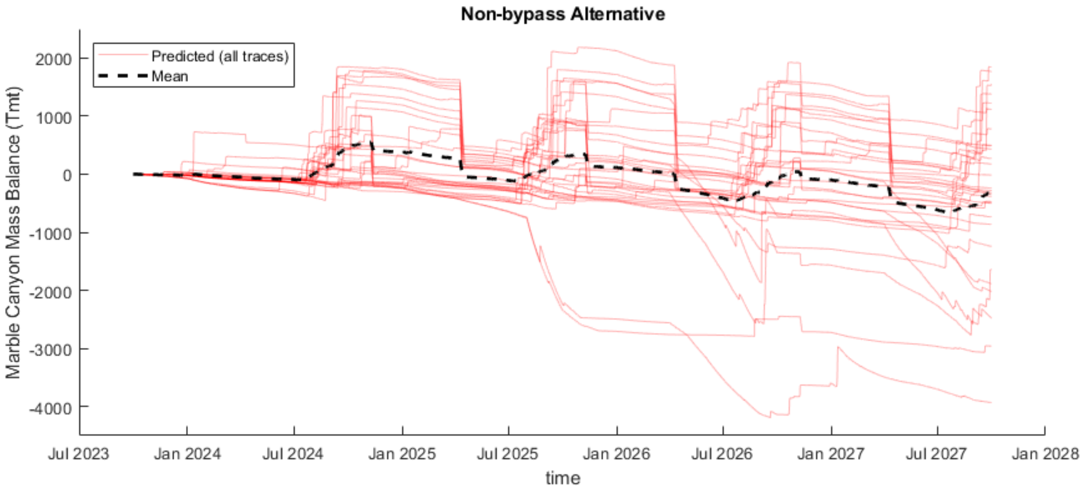


Figure 3-A19. Time series of Marble Canyon mass balance generated by the Sand Routing Model under the Non-Bypass Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces (Salter and Grams, 2024).

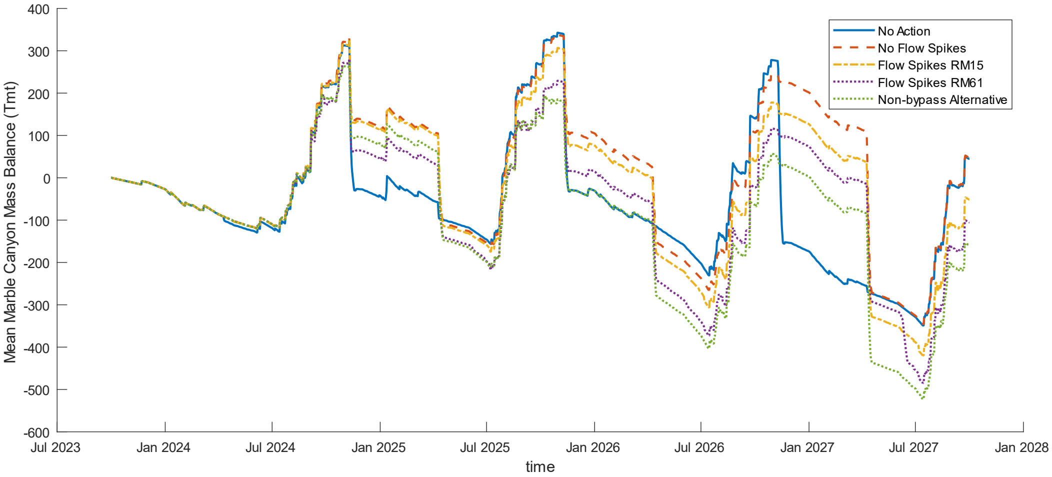


Figure 3-A20. Average Marble Canyon Sand Mass Balance for traces that under the Non-Bypass Alternative include non-bypass fluctuations (Salter and Grams, 2024).

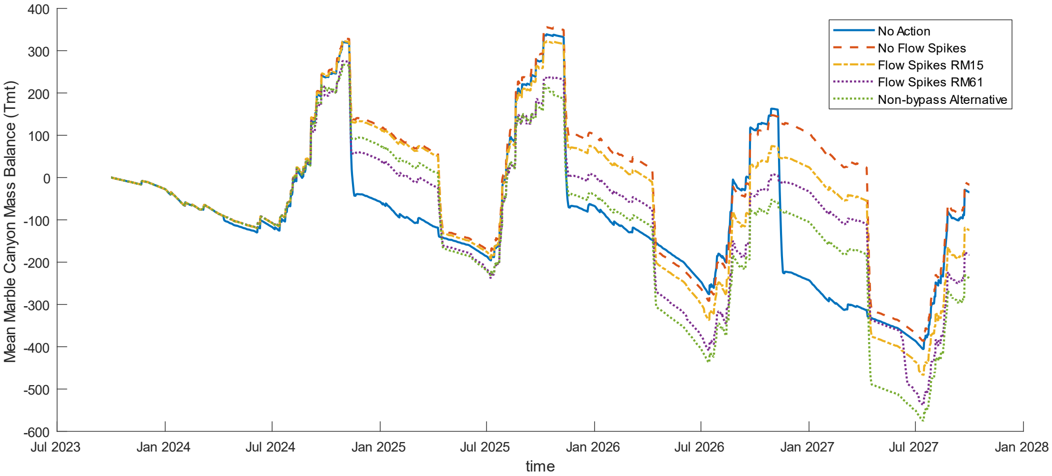


Figure 3-A21. Average Marble Canyon Sand Mass Balance for traces that under the Flow Spikes RM 61 scenarios include flow spikes (Salter and Grams, 2024).

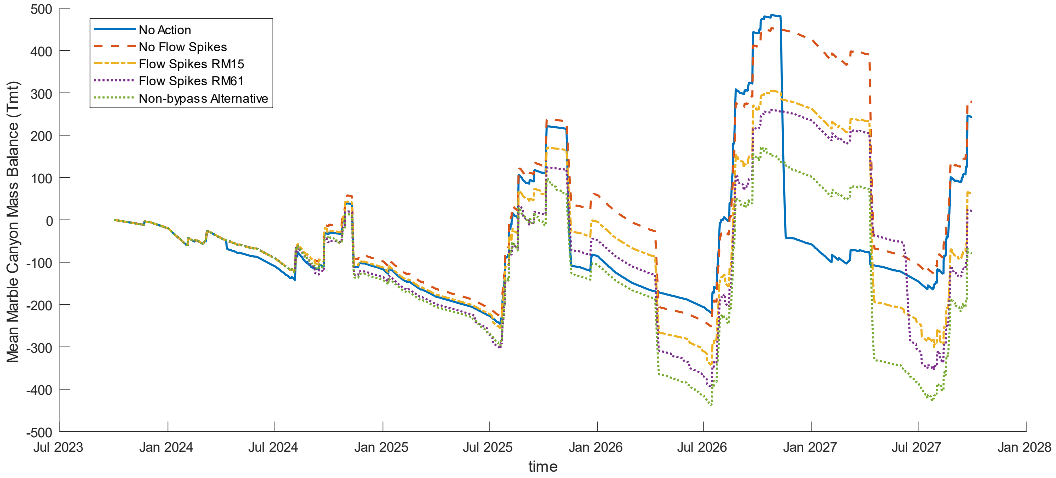


Figure 3-A22. Average Marble Canyon Sand Mass Balance for traces that under the Flow Spikes RM 15 scenarios include flow spikes (Salter and Grams, 2024).

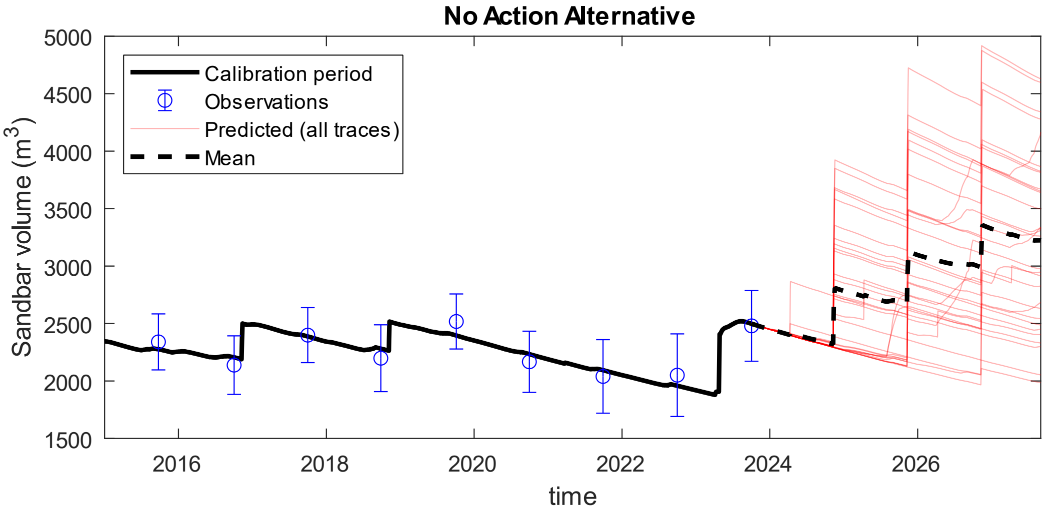


Figure 3-A23. Sandbar Model results for “No Action” Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces. Distinct upward steps in the mean sandbar size occur in the Fall, because this is when most HFEs are implemented under the No Action Alternative (Salter and Grams, 2024).

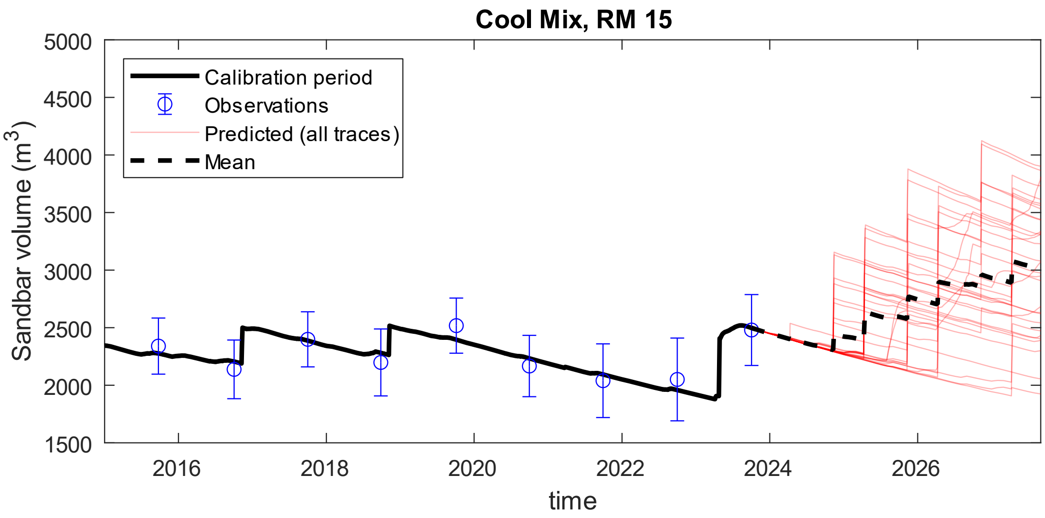


Figure 3-A24. Sandbar Model results for "Cool Mix, RM 15" Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces. The mean reflects HFE's implemented in both fall and spring, but individual traces with both in a single year are rare (Salter and Grams, 2024).

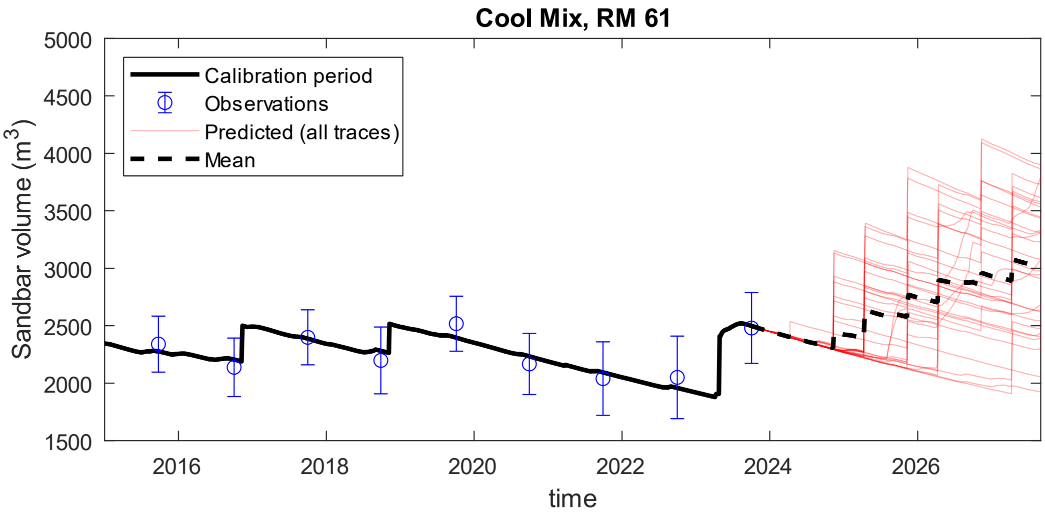


Figure 3-A25. Sandbar Model results for "Cool Mix, RM 61" Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces. The mean reflects HFEs implemented in both fall and spring, but individual traces with both in a single year are rare (Salter and Grams, 2024).

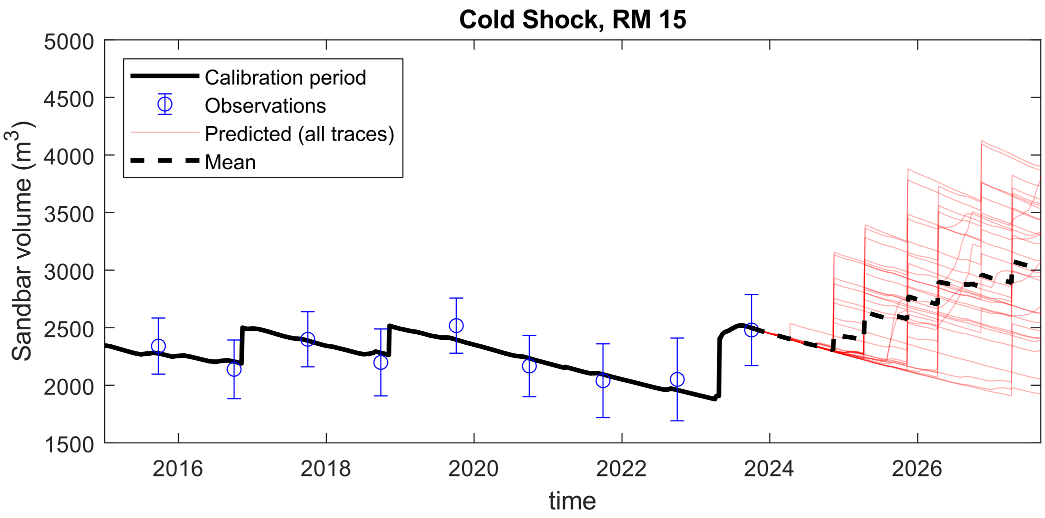


Figure 3-A26. Sandbar Model results for "Cold Shock, RM 15" Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces. The mean reflects HFEs implemented in both fall and spring, but individual traces with both in a single year are rare (Salter and Grams, 2024).

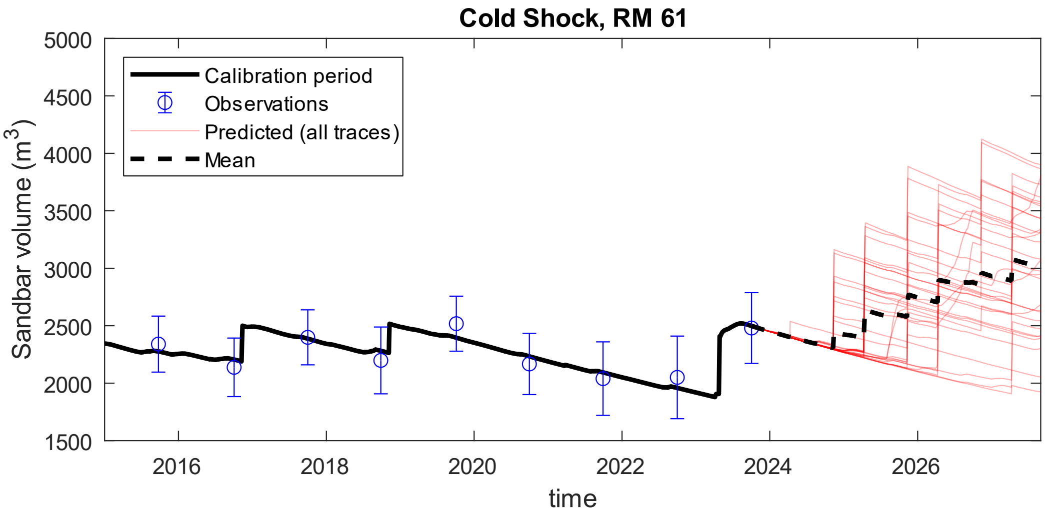


Figure 3-A27. Sandbar Model results for "Cold Shock, RM 61" Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces. The mean reflects HFEs implemented in both fall and spring, but individual traces with both in a single year are rare (Salter and Grams, 2024).

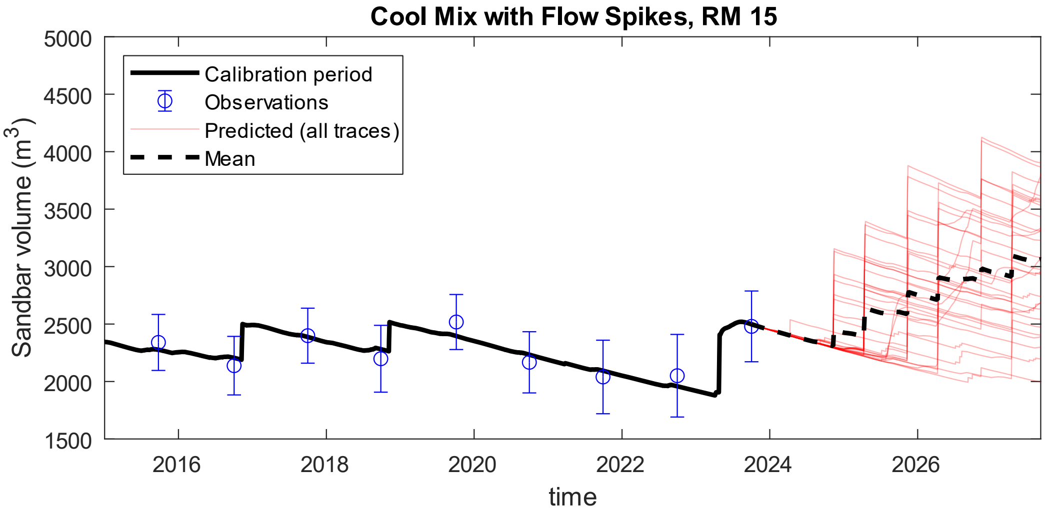


Figure 3-A28. Sandbar Model results for "Cool Mix with Flow Spikes, RM15" Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces. The mean reflects HFEs implemented in both fall and spring, but individual traces with both in a single year are rare (Salter and Grams, 2024).

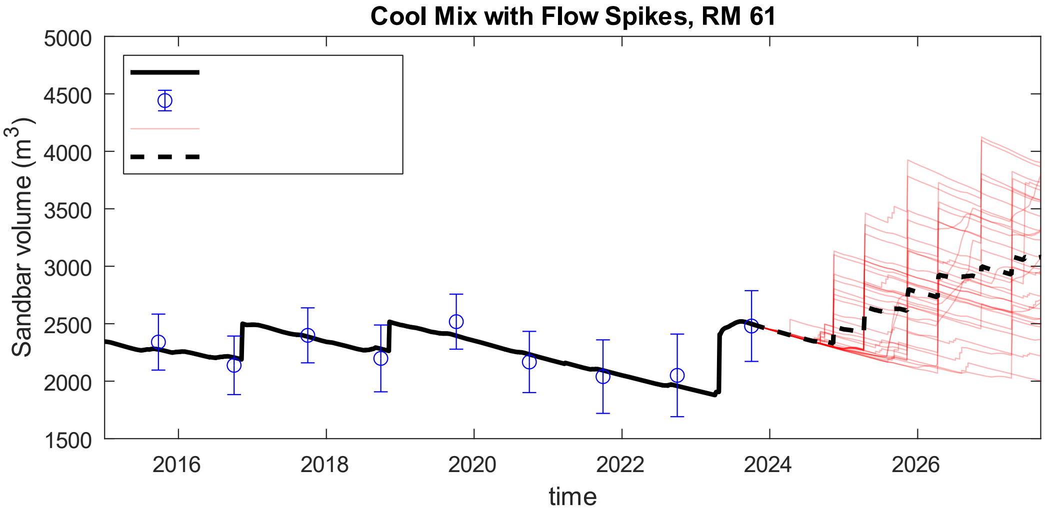


Figure 3-A29. Sandbar Model results for "Cool Mix with Flow Spikes, RM 61" Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces. The mean reflects HFEs implemented in both fall and spring, but individual traces with both in a single year are rare (Salter and Grams, 2024).

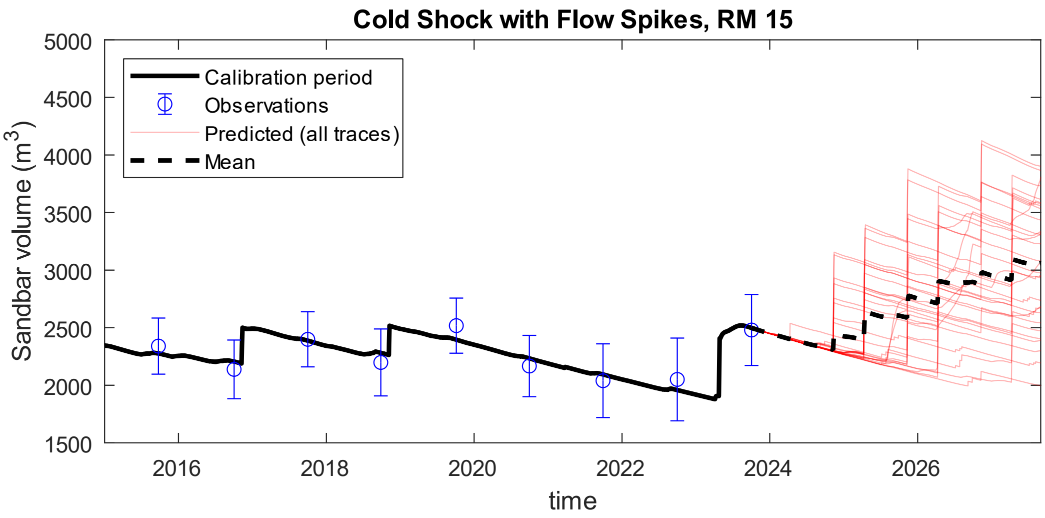


Figure 3-A30. Sandbar Model results for “Cold Shock with Flow Spikes, RM 15” Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces. The mean reflects HFEs implemented in both fall and spring, but individual traces with both in a single year are rare (Salter and Grams, 2024).

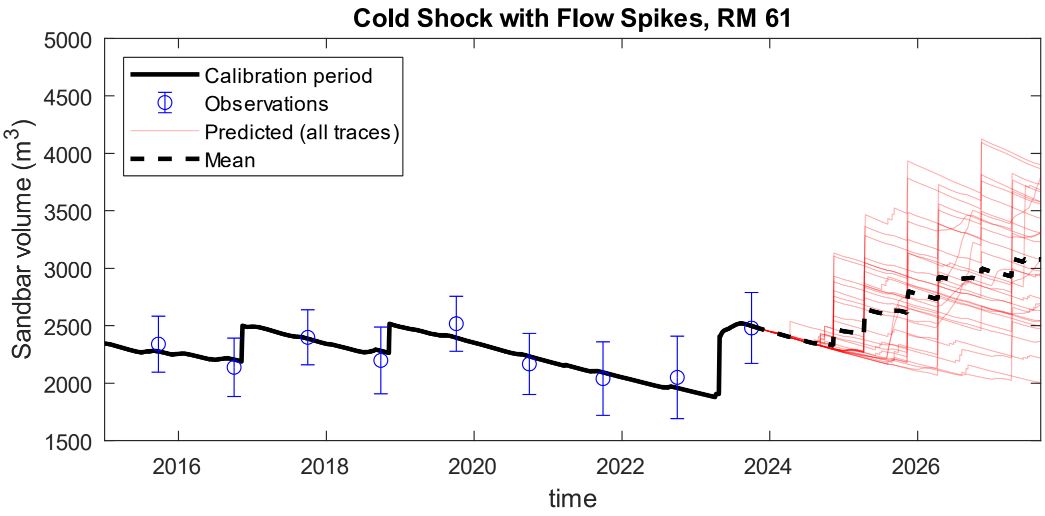


Figure 3-A31. Sandbar Model results for “Cold Shock with Flow Spikes, RM 61” Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces. The mean reflects HFEs implemented in both fall and spring, but individual traces with both in a single year are rare (Salter and Grams, 2024).

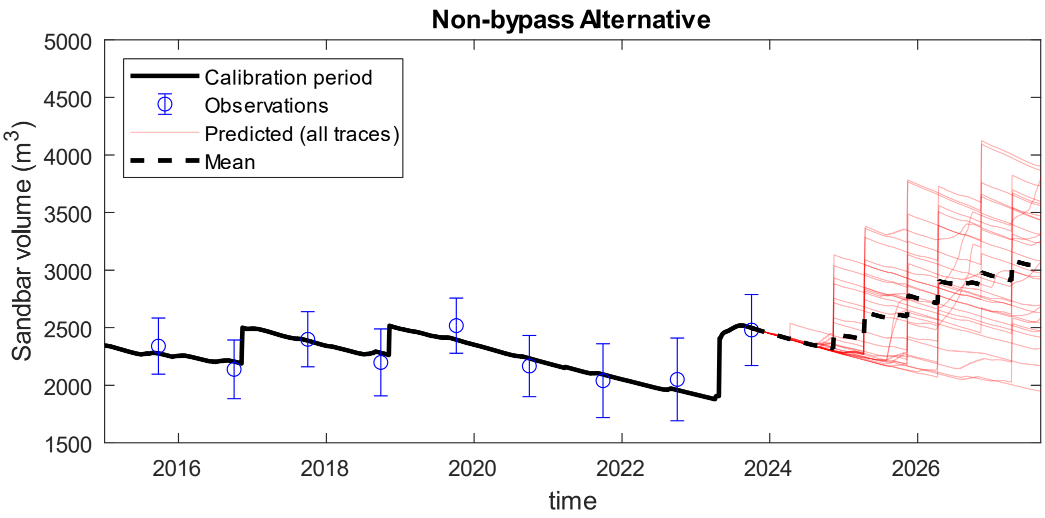


Figure 3-A32. Sandbar Model results for “Non-Bypass” Alternative. Red lines are individual traces, and the dashed black line is the mean of all traces. The mean reflects HFEs implemented in both fall and spring, but individual traces with both in a single year are rare (Salter and Grams, 2024).

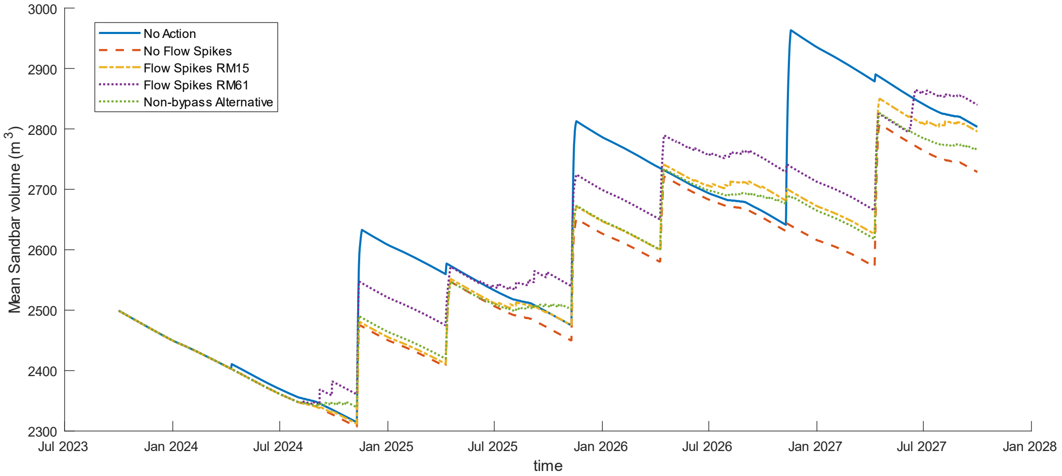


Figure 3-A33. Mean sandbar volume for traces that under the Non-Bypass Alternative include non-bypass fluctuations (Salter and Grams, 2024).

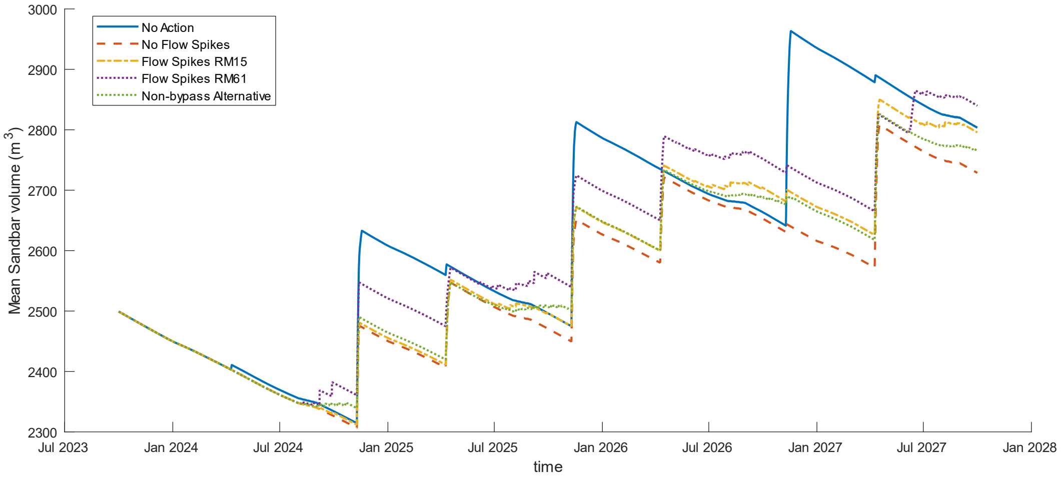


Figure 3-A34. Mean sandbar volume for traces that under the Flow Spikes RM 61 scenarios include flow spikes (Salter and Grams, 2024).

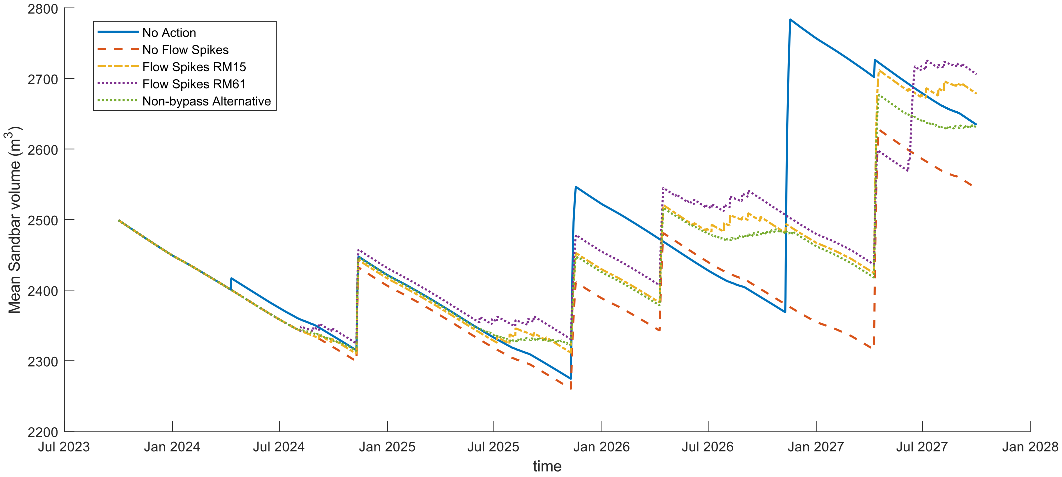


Figure 3-A35. Mean sandbar volume for traces that under the Flow Spikes RM 15 scenarios include flow spikes (Salter and Grams, 2024).

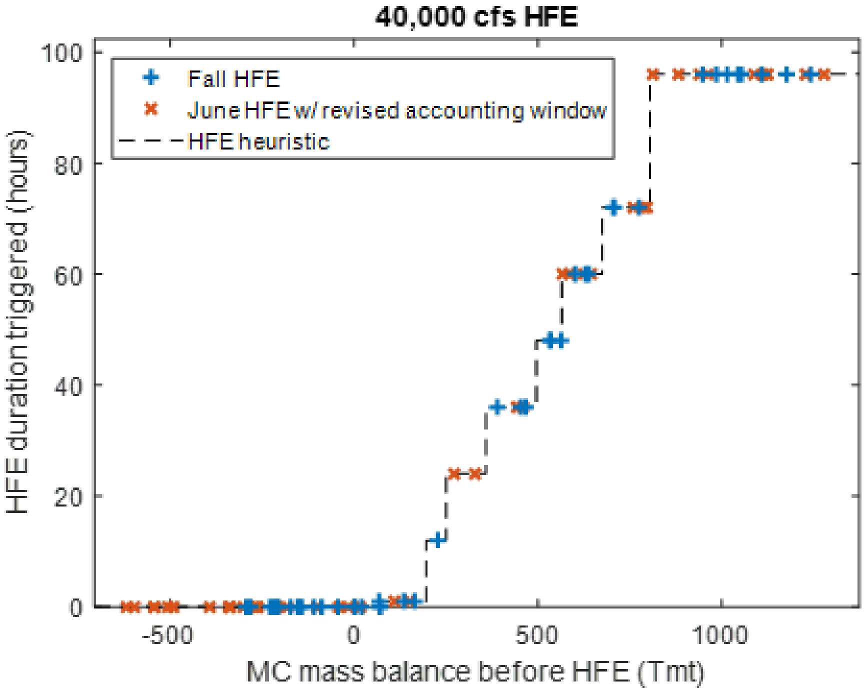


Figure 3-A36. Relationship between Marble Canyon mass balance and triggered HFE duration according to the Sand Routing Model. Dashed line is the heuristic relationship for predicting HFE duration on the basis of 1200 simulations.

Data Availability Statement:

Data generated during this study are published and available (Salter and Grams, 2024).

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IV. Modeling Impacts of Different Reservoir Management Scenarios on Smallmouth Bass (*Micropterus dolomieu*) Entrainment and Population Growth Rates

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Background and Methods

Smallmouth bass (SMB; *Micropterus dolomieu*) are a highly valued sport fish that have been introduced throughout the globe and have often spread extensively beyond their initial point of introduction (Loppnow and others, 2013). Within the Colorado River basin, SMB were historically introduced into many reservoirs, including Lake Powell, and have spread into many segments of river network above Lake Powell (Breton and others, 2015; Bestgen and Hill, 2016; Dibble and others, 2021). SMB invasion into rivers throughout the globe have been associated with substantial population declines, and in many instances, extirpations of native fish species (Brown and others, 2009; Loppnow and others, 2013). SMB are extremely capable predators able to consume many size classes of native fish of the Colorado River basin, including federally listed humpback chub (HBC *[Gila cypha]*; Johnson and others, 2008; Arena and others, 2012; Schake and others, 2014; Fernando and others, 2018; Ward and Vaage, 2019). In the upper Colorado River basin, SMB are considered the greatest threat to the persistence of threatened and endangered fish species (Johnson and others, 2008). SMB are also fecund and adaptable to a substantial range of environmental conditions (Edwards and others, 1983; Loppnow and others, 2013) and have successfully invaded rivers across multiple continents (Loppnow and others, 2013).

SMB were rarely observed in the Colorado River ecosystem below Glen Canyon Dam (GCD) prior to 2022 (Interagency SMB Taskforce presentation to the Technical Working Group, 2022); however, likely reproduction was identified for the first time in 2022 (Eppehimer and others, 2024; National Park Service, unpublished data). Low reservoir elevations in Lake Powell have likely led to modest increases in the entrainment of SMB, which, like most fish species, typically occupy the shallower parts of the water column in Lake Powell (Eppehimer and others, 2024). Lower reservoir elevations have also contributed to dramatic warming of water release temperatures making the river more suitable for SMB reproduction (Eppehimer and others, 2024), which likely occurred in 2022 and 2023.

General modeling

We used models from Eppehimer and others (2024) to analyze different reservoir operation alternatives developed by Reclamation as part of the Interim Guidelines Supplemental Environmental Impact Statement (SEIS; Bureau of Reclamation, 2024a) and LTEMP Long-term Experimental and Management Plan Supplemental Environmental Impact Statement (Bureau of Reclamation, 2024b). Outputs from these models include forecasts of daily water temperature, the SMB asymptotic population growth rate (i.e., lambda), and SMB entrainment rate from Lake Powell.

In the SMB population growth model, the GCD release temperatures (penstock or bypass jet tubes) used are estimated for every day of the year using a model that relies on spring inflow (April-July) into Lake Powell, day of year, and depth as predictors and was fitted to 225 Lake Powell temperature profiles from 2000-2021 (Andrews and Deemer, 2022; see Eppehimer and others, 2024). Downriver warming of water released from GCD is estimated using a model developed by Dibble and others, (2021) adapted from monthly to daily scale by calculating average daily solar insolation and daily air temperatures from the Page weather station (see Eppehimer and others, 2024). Daily average water temperatures are for the mainstem Colorado River only and do not account for backwaters that will be warmer or colder than the mainstem depending on seasonality. The amount of water that needs to be released through the river outlets and the penstocks will vary based on the elevation of the lake and the distribution of water temperatures through the water column (these factors determine the temperature of the water being released), the time of year (air temperature and solar radiation) and the daily discharge, all of which determines how quickly a given amount of water warms as it travels downriver (Mihalevich and others, 2020; Dibble and others, 2021).

The SMB population growth rate model is based on thermal suitability and assumes that the thermal regime is the factor that limits SMB recruitment (see Eppehimer and others, 2024 for modeling details). This model relies on a 16-month window beginning in January to calculate lambda. It requires more than 12 months because winter conditions are needed to estimate overwinter survival. It assumes a 16 °C daily average water temperature spawning initiation threshold, when the temperature doesn’t drop below 13.9 °C in the following week (Eppehimer and others, 2024). SMB have been observed laying eggs at water temperatures as low as 15 °C in some systems; however, water temperatures of 16 °C or greater are typically required for SMB to lay eggs (see Eppehimer and others, 2024). For example, in the Green and Yampa rivers, the earliest observed hatch was always after the first day when temperatures increased above 16 °C daily average during a seven-year study across three river reaches (Bestgen and Hill, 2016).

In addition, a thermal regime >16 °C is needed for young of year to measurably grow during the growing season, since SMB in rivers ~16 °C would be unlikely to grow large enough to survive the winter (Shuter and others, 1980; Dudley and Trial, 2014).

The SMB entrainment model estimates the expected number of adult SMB propagules per year that are entrained through GCD from Lake Powell and survive (see Eppehimer and others, 2024 for modeling details). The SMB entrainment model is run on 12-month time step beginning in January.

Interim Guideline SEIS modeling

To estimate the potential changes in the number of entrained SMB through GCD and released into Lees Ferry, and the potential population growth rate of SMB in both Lees Ferry (River Mile [RM] 0) and the Colorado River at RM 61 (just upstream from the Colorado-Little Colorado River [LCR] confluence), we applied models (see Eppehimer and others, 2024) to simulate expectations under the 90 Colorado River Mid-term Modeling System (CRMMS) hydrologic traces (30 traces modeled at 80, 90, and 100% of the ensemble streamflow predictions (ESP), 90 total) to which the No Action and Proposed Action rules for water storage and release from Lake Powell in the Interim Guideline SEIS were applied.

Results of Analyzing Interim Guideline SEIS Alternatives

Glen Canyon Dam smallmouth bass entrainment

On average, SMB entrainment and passage through GCD into the Lees Ferry tailwater reach is expected to be less than 50 propagules per year across both SEIS scenarios from 2024-2026, but more extreme entrainment rates (>100 propagules per year) are possible in 2025 and 2026 (Figure 4-1; Eppehimer and others, 2024). SMB entrainment rates are expected to be similar between No Action and Proposed Action Alternatives under most, but not all hydrologic traces (Figure 4-2; Eppehimer and others, 2024). For example, under dry hydrologic conditions, the Action Alternative is expected to increase SMB entrainment relative to No Action (Figure 4-2).

Smallmouth bass population growth rate

Forecasted SMB population growth rate (lambda) was similar, on average, between No Action and Proposed Action under the SEIS from 2024-2026, whether forecasted RM 0 or RM 61 (Figure 4-3; Eppehimer and others, 2024). The number of traces in which SMB population growth (lambda) was predicted to occur is very similar between No Action and Proposed Action (Table 4-1). Over the years analyzed, 2-18% of the hydrologic traces predict population growth at RM 0 with the majority of those traces predicting high growth rates (lambda > 2; Table 4-1; Figure 4-3).

Over the years analyzed, 10-26% of the hydrologic traces predict population growth at RM 61 with the majority of those traces predicting high growth rates (lambda > 2; Table 4-1; Figure 4-3). Forecasted population growth rates at RM 61 are higher than those at RM 0 due to downriver warming (Figure 4-3). Under most hydrologic traces, there was very little relative difference in SMB population growth between No Action and Proposed Action Alternatives (Figure 4-4; Eppehimer and others, 2024).

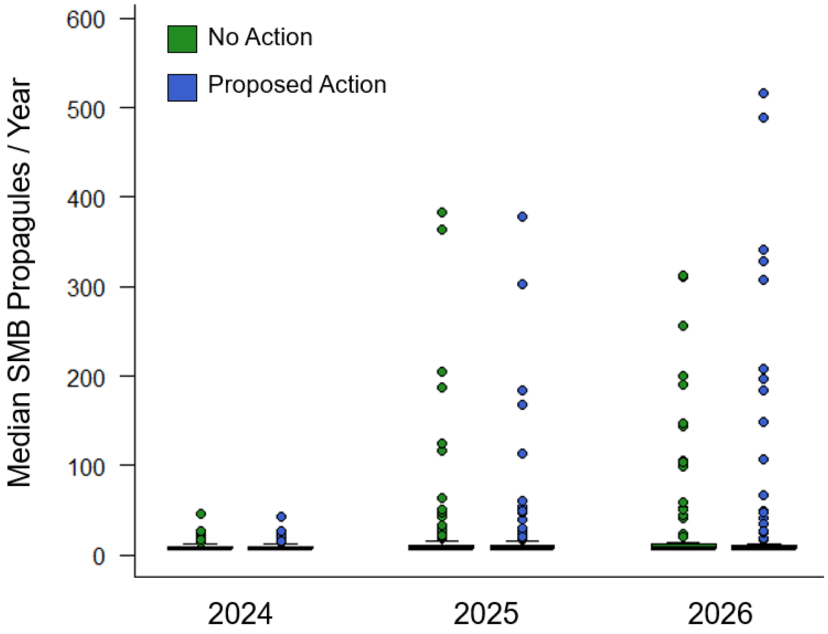

Figure 4-1. Forecasts of the median number of SMB entrained per year under the SEIS No Action (green; presented first from left to right) and Proposed Action (blue; presented second from left to right). For each of the 90 hydrologic traces, we calculated the median forecasted entrainment and summarized these results using a box and whisker plot in which the dark line represents the median, the boxes represent the upper and lower 25% quantiles, and the whiskers extended to twice the interquartile range with dots representing traces with more extreme values.

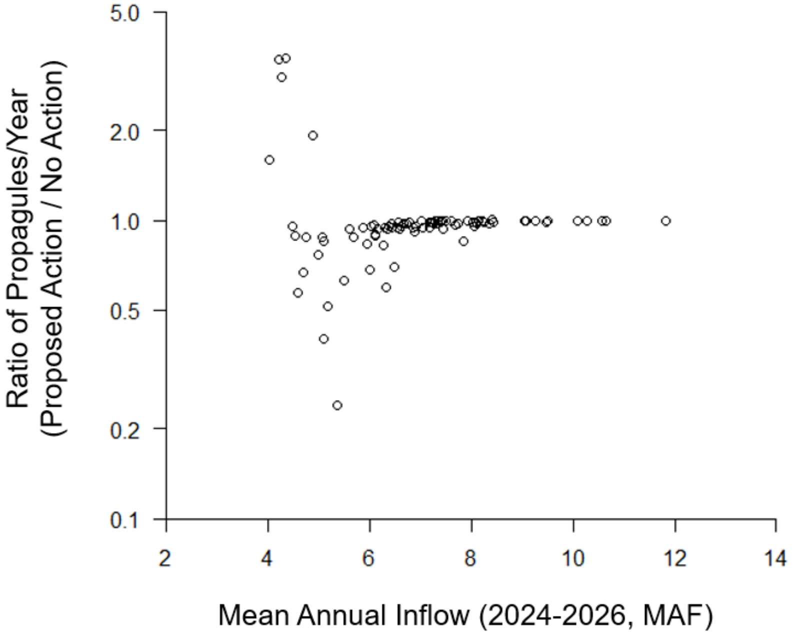

Figure 4-2. Ratio in forecasted smallmouth bass propagules between Proposed Action and No Action Alternatives. For each of the 90 hydrologic traces, we calculated the ratio of forecasted median propagules entrained from 2024-2026 and plotted it versus the mean annual inflow from those years.

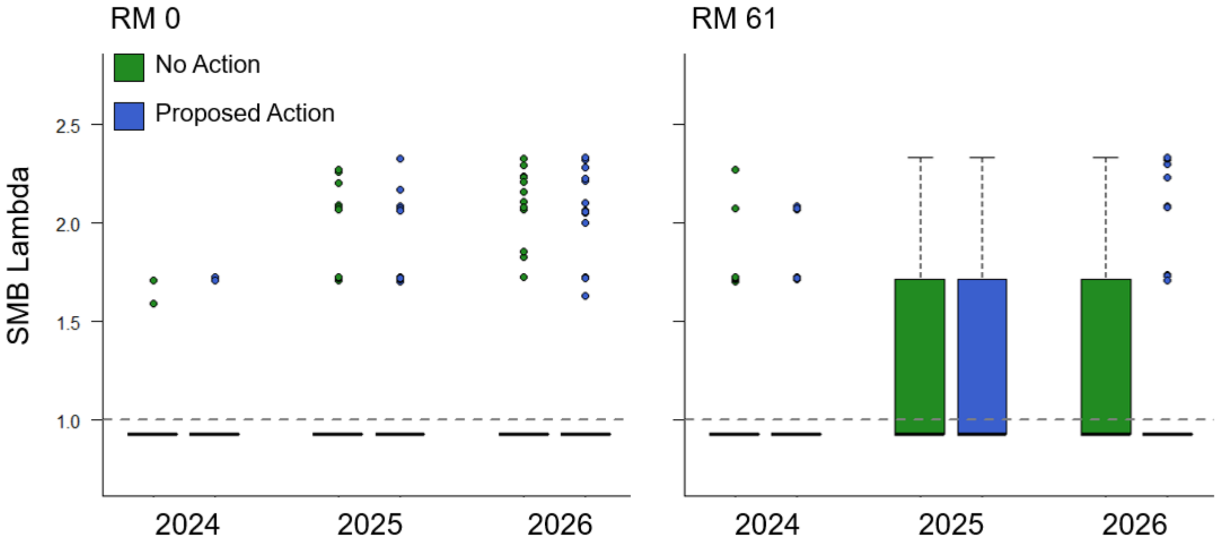

Figure 4-3. Forecasts of the potential annual SMB population growth rate (lambda) at RM 0 and RM 61 under No Action (green; presented first from left to right) and Proposed Action (blue; presented second from left to right) Alternatives. Lambda >1 indicates population growth. For each of the 90 hydrologic traces, we estimated population growth rate based on forecasted daily water temperature and summarized these results using a box and whisker plot in which the dark line represents the median, the boxes represent the upper and lower 25% quantiles, and the whiskers extended to twice the interquartile range with dots representing traces with more extreme values. Note: although the interquartile range for RM 61 Proposed Action 2026 decreased relative to No Action, the mean, median, and number of traces with lambda >1 are still very similar.

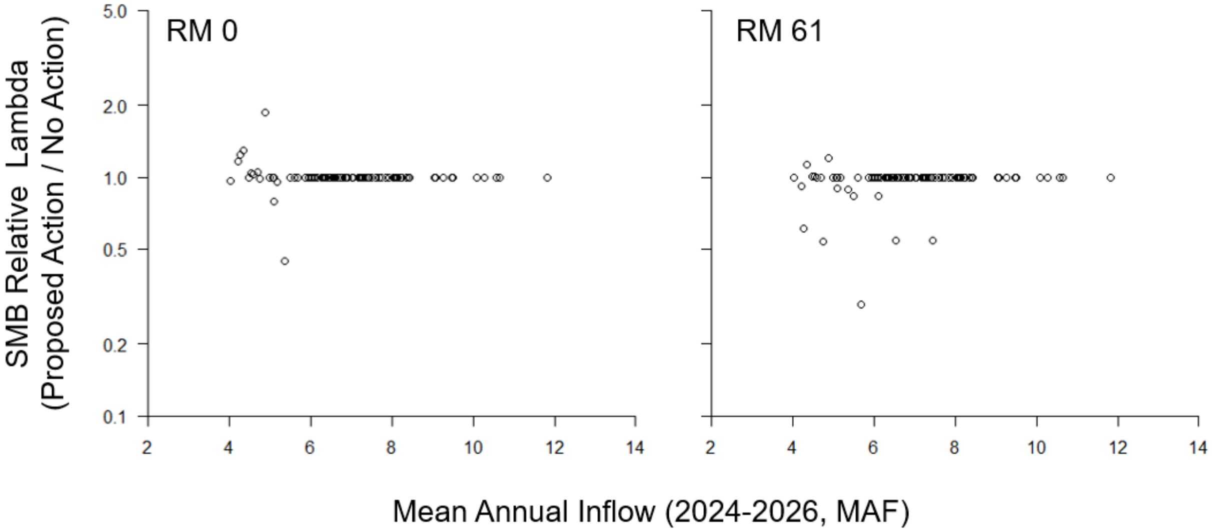

Figure 4-4. Difference in forecasted potential annual SMB population growth rate (lambda) at RM 0 and Rm 61 under Proposed Action and No Action Alternatives. For each of the 90 hydrologic traces, we calculated the ratio of the expected three-year (2024-2026) population growth rates and plotted it versus the mean annual inflow from those years.

Table 4-1. Percent of traces (rounded to the nearest %, out of 90 traces total) with predicted SMB population growth (lambda >1) for No Action and Proposed Action Alternatives by target location (RM 0 and RM 61) and year (2024-2026).

		% of Traces with SMB Lambda >1	
Location	**Year**	**No Action**	**Proposed Action**
RM 0	2024	2	2
RM 0	2025	13	13
RM 0	2026	18	18
RM 61	2024	16	10
RM 61	2025	26	26
RM 61	2026	26	24

LTEMP SEIS Modeling

To estimate the potential population growth rate of SMB at RM 15 and RM 61, we applied models (see Eppehimer and others, 2024) to simulate expectations under the 30 CRMMS hydrologic traces (30 traces at 100% ensemble streamflow prediction [ESP]) to which the No Action and SMB Alternative rules for water storage and release from Lake Powell in the LTEMP SEIS were applied.

To run the model for 2027 we had to add inflow, outflow, and elevation for October 2027 – April 2028. For water year 2028, we assumed 8-million-acre feet (maf) annual inflows following monthly volumes determined by a log transformed linear model fit to 2000-2021 historic inflows. For water year 2028, we assumed 7.48 maf annual outflows with monthly volumes determined by LTEMP EIS guidelines. Elevations were calculated using the CRSS water balance equation for Lake Powell given a starting elevation (September 2027) and subsequent monthly inflows and outflows. Given the minimal variation in monthly inflow and outflow during the October to April intervals and the fact that this period is primarily used to calculate starvation days, (Eppehimer and others, 2024) which are primarily a function of reservoir elevations, these assumptions have minimal impacts on lambda estimates and would not be expected to change the bypass required under a SMB Alternative.

Analysis of flow disturbance on SMB lambda was estimated for both alternatives with flow spikes and the Non-Bypass Alternative. This analysis used a Lees Ferry tailwater discharge-velocity model with 5x5 m resolution (Nelson and others, 2016; Kaplinski and others, 2022a, b; Wright and others, 2024). No such model exists for downriver sections of the Colorado River in Grand Canyon, so for a given GCD discharge we assumed the proportions of river wetted area and proportions of water velocities were the same for all reaches.

We estimated SMB spawning habitat disturbance under GCD flow scenarios assuming nesting in habitat with water velocity ≤0.1 meters per second (m/s; Winemiller and Taylor, 1982; Lukas and Orth, 1995; Miller and Brewer, 2021) and assuming drying or velocities >0.3 m/s (Lukas and Orth, 1995; Miller and Brewer, 2021) would cause nest abandonment by guarding males and subsequent nest failure, assuming 100% mortality of offspring (Winemiller and Taylor, 1982; Lukas and Orth, 1995; Knotek and Orth, 1998).

This model used habitat available at baseflow conditions (incorporating load following discharges) and habitat disturbance by subsequent increases or decreases in discharge. SMB can renest multiple times during a spawning season (Lukas and Orth, 1995), so we assumed three nesting opportunities per spawning season allowing SMB to renest if their nest was disturbed by flows.

Flow disturbance effect was estimated using an equation for proportion of offspring remaining for a given flow: ((1-x)+x*(1-x)*2/3+x*x*(1-x)*1/3), where x represents estimated proportion of spawning habitat disturbed. This was then multiplied by fecundity.

Results of Analyzing LTEMP SEIS Alternatives

Smallmouth bass population growth rate

The model predicts that SMB population growth at RM 15 is less than 1 in all four years in 5 out of 30 traces under the No Action Alternative. Across 30 traces, each lasting 4 years, there were only 10 total years under the No Action Alternative in which SMB populations were predicted to increase (Figure 4-5A). The Cool Mix Alternatives resulted in no predicted population growth for 100% of traces and years. The Cold Shock Alternative is expected to allow for population growth in 1 trace in 2026 and 1 trace in 2027. The addition of flow spikes reduced these estimated lambdas but did not stop population growth. Similarly, the within powerplant capacity flow fluctuations (Non-Bypass) reduced estimated lambdas when compared to No Action but did not stop population growth.

The model predicts that SMB population growth at RM 61 is less than 1 in all four years in 7 out of 30 traces under the No Action Alternative. Due to downriver warming of water temperatures, more traces (and more years within traces) have population growth at this location than at RM 15. Across 30 traces, each lasting 4 years, there were only 13 total years under the No Action Alternative in which SMB populations were predicted to increase at RM 61 (Figure 4-5B). The Cool Mix Alternatives resulted in no predicted population growth for 100% of traces and years. Under the Cold Shock Alternative there were 6 years in which SMB populations were predicted to increase. The addition of a flow spikes reduced these estimated lambdas but did not stop population growth. Similarly, the within powerplant capacity flow fluctuations (Non-Bypass) reduced estimated lambdas when compared to No Action but did not stop population growth.

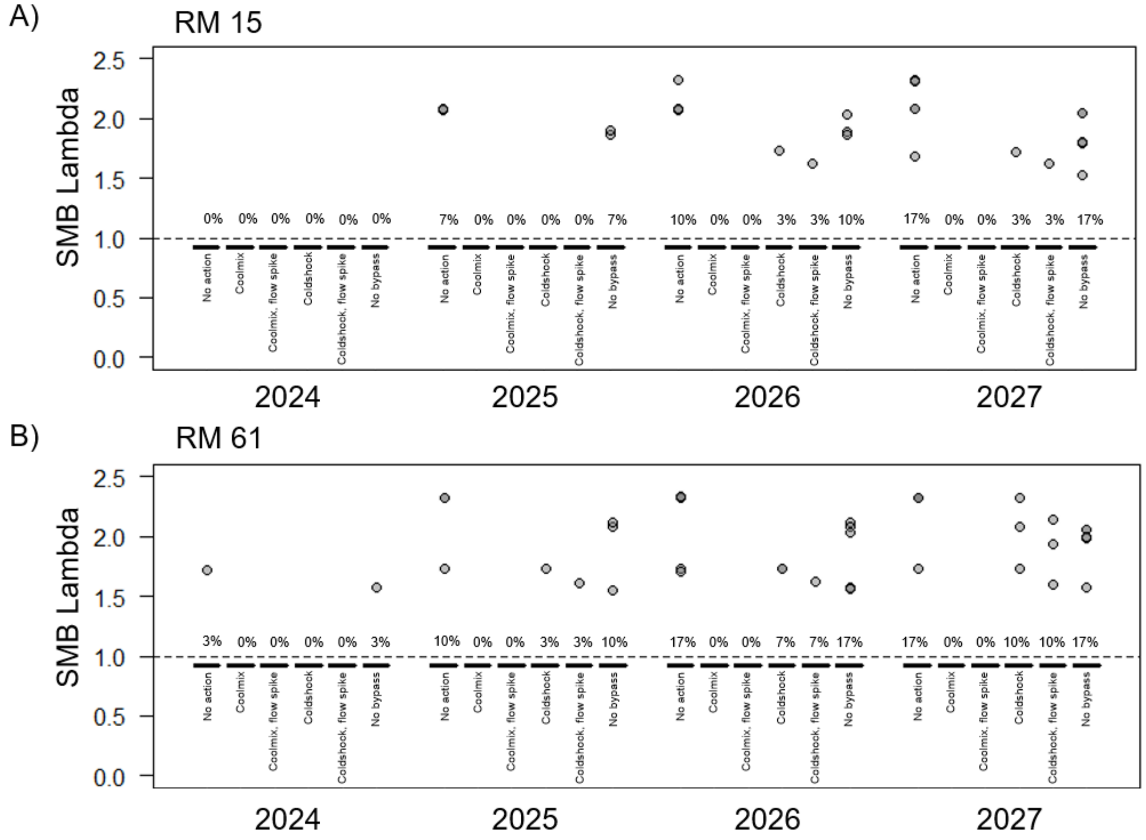

Figure 4-5. Forecasts of the potential annual SMB population growth rate (lambda) at A) RM 15 and B) RM 61 of the Colorado River under No Action, Cool Mix, Cool Mix with flow spike, Cold Shock, Cold Shock with flow spike, and Non-Bypass Alternatives. Grey, horizontal dashed line denotes lambda = 1. Lambda >1 indicates population growth. For each of the 30 hydrologic traces, we estimated population growth rate based on forecasted daily water temperature and summarized these results using a box and whisker plot in which the dark line represents the median, the boxes represent the upper and lower 25% quantiles, and the whiskers extend to twice the interquartile range with dots representing traces with more extreme values. All box and whisker plots' interquartile ranges are below 1, and therefore appear compressed. Only extreme values (dots) are above 1. The numbers above the dashed, horizontal 1 line represent the percent of traces (rounded to the nearest percent; out of 30 traces) in which lambda was predicted to be >1 for that year and scenario.

Data Availability Statement:

Data generated during this study are published and available (Eppehimer and Yackulic, 2024).

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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V. Modeling Impacts of Glen Canyon Dam Operations Scenarios of the Interim Guidelines SEIS and LTEMP SEIS on Sand Exposure for Aeolian Landscape and Cultural Site Resources

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Background and Methods

The movement of river-sourced sediment by wind is an important process in the Colorado River Ecosystem (CRe) because windblown deposition of sediment provides favorable habitat for endemic vegetative species, such as sand dropseed (*Sporobolus cryptandrus*) and dunebroom (*Parryella filifolia*), and results in in-situ burial and preservation of archaeological sites that line the river corridor and which are above the elevation of regularly occurring post-dam floods of the Colorado River (East and others, 2016; Cook and others, 2019). In the absence of such windblown sediment deposition, these archaeological sites are more susceptible to loss from gully erosion and overland rainfall runoff. To be mobilized by wind, river sand must be both bare (i.e., not covered in vegetation) and dry (i.e., exposed for an appreciable amount of time since last being inundated by the Colorado River).

Cultural resource preservation potential in Grand Canyon National Park (GCNP) increases with larger values of exposed, dry Colorado River sand that is susceptible to windblown (aeolian) transport. We conducted modeling to determine the area of exposed, dry river sand between Glen Canyon Dam (GCD) and Bright Angel Creek within the CRe. The model used here predicts the area of bare, dry sand for the upper ~103 miles of Grand Canyon between GCD and Phantom Ranch/Bright Angel Creek. It uses a timeseries of daily maximum discharge from GCD, field-derived maps of bare sand from a combination of multi- and single-beam sonar, total station, and aerial photo interpretation, in combination with hydraulic models of inundation extent to derive the total exposed bare sand area for a given discharge from GCD. This initial bare sand area is modified to incorporate its exposure time, as longer exposure times result in progressively drier, and thus more transportable, sand. The model is detailed in Kasprak and others (2021) and the modifications based on drying time follow Sankey and others (2022). See Kasprak and others (2024) for the associated data.

Model Assumptions

The model used here was developed with, and makes predictions of, dry bare sand for the reach of the CRe between GCD (River Mile [RM] -16) and Bright Angel Creek (RM 87). It was not developed to also predict bare sand extent in areas downstream from Bright Angel Creek.

Additionally, the drying time component of the model is based on empirical field data of effects of sand drying on aeolian sediment transport collected during March 2021 at Lees Ferry. Locationally-specific sand drying rates depend on numerous other factors that may vary spatially and seasonally, including temperature, solar insolation intensity, and precipitation, among others.

The model does not consider effects of implementing High Flow Experiments (HFEs; controlled floods) on the availability of river sand for aeolian transport. HFEs that rebuild sandbars will increase the supply of windblown sand for archaeological sites that are downwind from river sandbars (Sankey and others, 2018).

At present, this model also does not consider effects of variability in wind. Aeolian sediment transport rates increase with frequency of winds above threshold transport velocities, which are more common from March through July of each year (Caster and others, 2014). Longer sand exposure times during the spring and summer seasons combined with HFEs may additionally increase the supply of sand for downwind archaeological sites.

Results of Analyzing Interim Guideline SEIS Alternatives

Figure 5-1 shows the relative percent difference for implementing the Proposed Action Alternative vs. No Action Alternative. Across 90 modeled ensemble streamflow predictions, the mean and median exposed sand areas are very similar between the Proposed Action Alternative and No Action Alternative (Table 5-1).

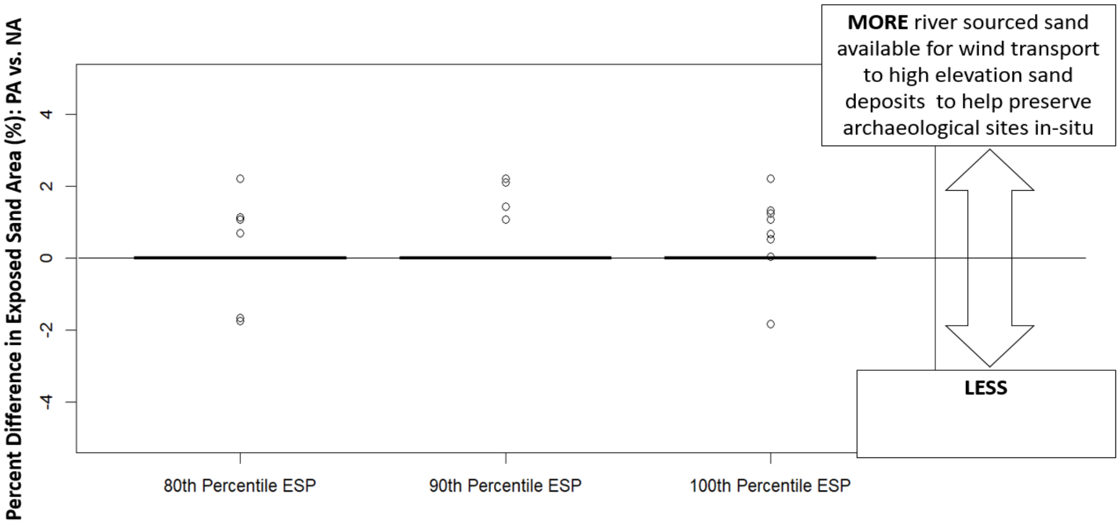

Figure 5-1. Percent difference in exposed sand area (%), Proposed Action Alternative vs. No Action Alternative. Positive values indicate more, and negative values indicated less, river sourced sand available for wind transport to high elevation sand deposits to help preserve archaeological sites in situ. Percent difference in exposed sand area is calculated for individual ensemble streamflow prediction (ESP) traces as Percent Change = [(Proposed Action Alternative - No Action Alternative)/(Proposed Action Alternative + No Action Alternative)/2)] * 100.

Table 5-1. Results of exposed sand area modeling under the three bins of ensemble streamflow predictions.

Ensemble Streamflow Bin	Mean Exposed Sand Area (m^2) *No Action alternative*	Median Exposed Sand Area (m^2) *No Action alternative*	Mean Exposed Sand Area (m^2) *Proposed Action alternative*	Median Exposed Sand Area (m^2) *Proposed Action alternative*
80th Percentile	1,572,250	1,518,037	1,581,239	1,541,849
90th Percentile	1,527,976	1,507,151	1,534,520	1,507,151
100th Percentile	1,489,311	1,507,151	1,506,440	1,507,151

Results of Analyzing LTEMP SEIS Alternatives

Figure 5-2 shows box and whisker plots summarizing the median daily exposed sand area (m^2) predicted for each of the alternative scenarios. The median daily exposed sand area is predicted from hourly releases (generated as input for resource models) for each of the alternative scenarios for 30 hydrological traces (ensemble streamflow prediction (ESP) 100%). Figure 5-3 shows box and whisker plots summarizing the percent difference in exposed sand area (%) for each of the alternative scenarios relative to the No Action Alternative. In general, results suggest that the daily exposed sand area is not predicted to differ substantially from the No Action alternative for each of the alternative scenarios examined here.

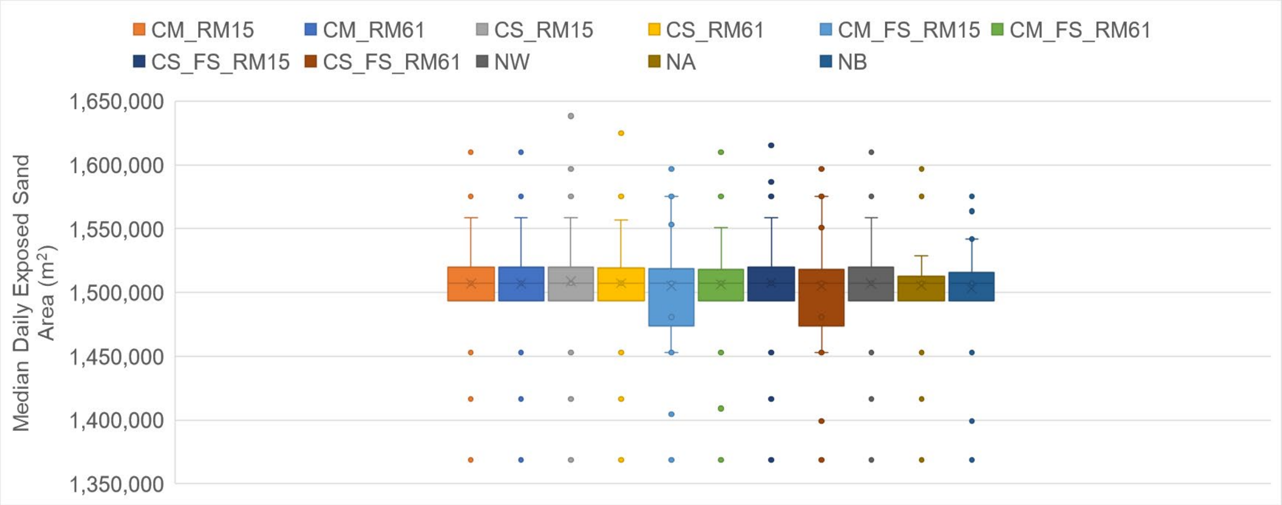

Figure 5-2. Median daily exposed sand area (m^2) for each of the alternative scenarios. Larger values indicate more river sourced sand available for wind transport to high elevation sand deposits to help preserve archaeological sites in situ.

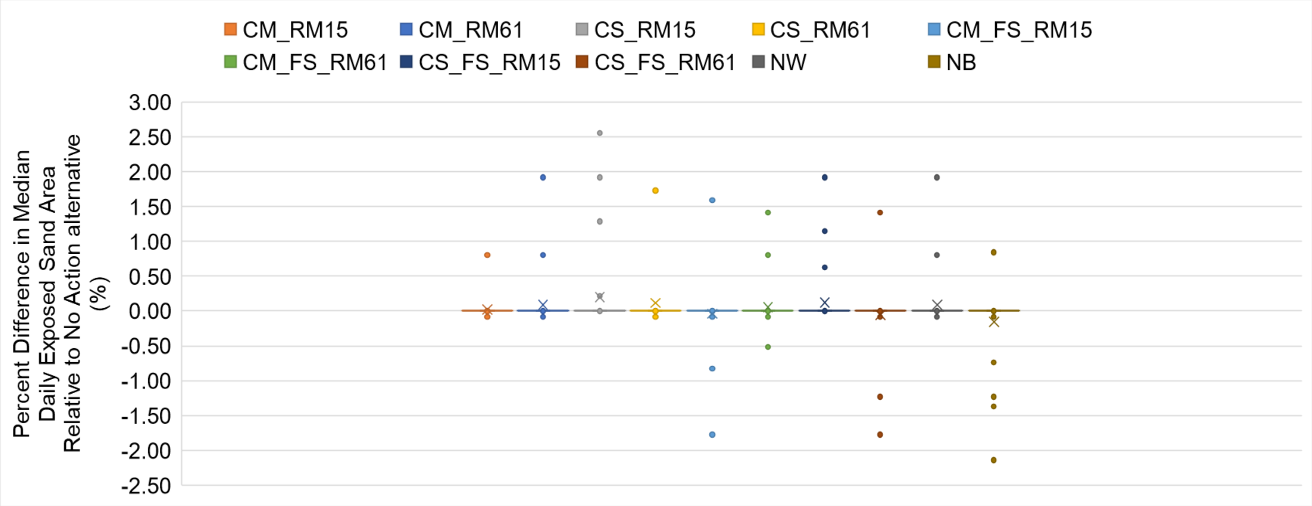

Figure 5-3. Percent difference in exposed sand area (%) for each of the alternative scenarios relative to the No Action Alternative. Positive values indicate more, and negative values indicate less, river sourced sand available for wind transport to high elevation sand deposits to help preserve archaeological sites in situ. Percent difference in exposed sand area is calculated for individual ESP traces as Percent Change = [(Alternative scenario X - No Action Alternative)/(Alternative scenario X + No Action Alternative)/2)] * 100.

Data Availability Statement:

Data generated during this study are published and available (Kasprak and others, 2024).

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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VI. Modeling Recreation Impacts of Glen Canyon Dam Releases

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Introduction

We estimate the net economic value of recreational angling and whitewater rafting trips in Glen and Grand Canyons, respectively, in support of the Interim Guidelines (Supplemental Environmental Impact Statement) SEIS and Long-term Experimental and Management Plan Supplemental Environmental Impact Statement (LTEMP SEIS). This analysis is similar to the recreation economic analysis for the LTEMP EIS (Gaston and others, 2015). Models were informed from past survey research and used to project the change in net economic value for angling in Glen Canyon and whitewater rafting in Grand Canyon comparing the Action and No Action Alternative scenarios. No analysis was completed for reservoir levels, water-based day use in Glen Canyon, and recreational rafting in the Lower Grand Canyon below Diamond Creek. Water-based day use in Glen Canyon has historically not been impacted by river flow (Bishop and others, 1987).

Methods

For Glen Canyon anglers, a flow function (Equation 1) was estimated from angler surveys (Bishop and others, 1987). The angler surveys use different river flow scenarios to estimate the net economic value of an individual trip, as a function of river flow. The function used to estimate net economic value are for conditions where within-day fluctuations are less than 10,000 cubic feet per second (cfs), consistent with the evaluated alternatives.

$$WTP\begin{cases} if\ flow\ \leq 10{,}000;\ 43.1429 + 0.0082857 \times flow \\ if\ 10{,}000 < flow \leq 25{,}000;\ 147.333 - 0.0021333 \times flow \\ if\ flow > \ 25{,}000;\ 164.00 - 0.0028 \times flow \end{cases} \tag{1}$$

$WTP = net\ economic\ value\ (1985\$\ per\ trip)$

$Flow = release\ from\ Glen\ Canyon\ Dam\ in\ cubic\ feet\ per\ second\ (cfs)$

Equation 1 is used to then estimate the economic value for angling in Glen Canyon on an individual trip basis. This is accomplished by estimating the average river flow within a month for each alternative and hydrology provided (e.g., the 80%, 90% and 100% of streamflow levels predicted by the ensemble streamflow prediction (ESP) forecast). The average monthly river flow is the mean flow across all hours within a month. The average flow is used in Equation 1 to estimate the net economic value of an individual angler on a single trip within a month.

The estimated angler trips per month (D. Rogowski, Arizona Game and Fish Department, written communication, February 2023) are then multiplied by the net economic value to obtain the aggregate net economic value for angling.

Net economic value is indexed to 2022 dollars using the consumer pricing index (U.S. Bureau of Labor Statistics, 2023).

For Grand Canyon whitewater rafters, a flow function (Equation 2) was estimated from whitewater rafter surveys (Bishop and others, 1987; Neher and others, 2017). The whitewater surveys use different river flow scenarios to estimate the net economic value of an individual trip, as a function of river flow. The function used to estimate net economic value are for conditions where within day fluctuations are less than 10,000 cfs, consistent with the Action and No Action Alternatives. In the absence of an updated primary study, the relationship between flow and economic value for private whitewater rafting was used for all trips in Grand Canyon.

$$WTP \begin{cases} if\ flow\ \le 13{,}000;\ 341.375 + 0.0681 \times flow \\ if\ 13{,}000 < flow \le 22{,}000;\ 1003.1 + 0.0172 \times flow \\ if\ flow > 22{,}000;\ 1234.00 - 0.0160 \times flow \end{cases} \tag{2}$$

$WTP = net\ economic\ value\ (2015\$\ per\ trip)$

$Flow = release\ from\ Glen\ Canyon\ Dam\ in\ cfs$

Equation 2 is used to then estimate the economic value for whitewater rafting in Grand Canyon on an individual trip basis. This is accomplished by estimating the average river flow within a month for each alternative and hydrology provided (e.g., the 80%, 90% and 100% of streamflow levels predicted by the ESP forecast). The average monthly river flow is the mean flow across all hours within a month. The average monthly flow is used in Equation 2 to estimate the net economic value of an individual whitewater trip within a month. The estimated individual whitewater trips per month (National Park Service, 2006) are then multiplied by the net economic value to obtain the aggregate net economic value for whitewater rafting. Net economic value is indexed to 2022 dollars using the consumer pricing index (U.S. Bureau of Labor Statistics, 2015).

Results

Results are the net economic value in 2022 nominal dollars for recreational angling in Glen Canyon and whitewater rafting on Grand Canyon by month for each alternative and hydrologic traces in the LTEMP SEIS and Interim Guidelines SEIS (Bair, 2024). We illustrate results for the estimated net changes in economic value across months for each ESP when comparing the proposed Action and No Action Alternatives in the Interim Guidelines SEIS.

Figures 6.1 and 6.2 illustrate this for angler and whitewater trips, respectively, and highlight the 10th, 50th, and 90th percentile. The data publication that accompanies this chapter includes the monthly aggregate net economic values for angling and whitewater trips for each alternative and hydrology provided for each alternative (Bair, 2024).

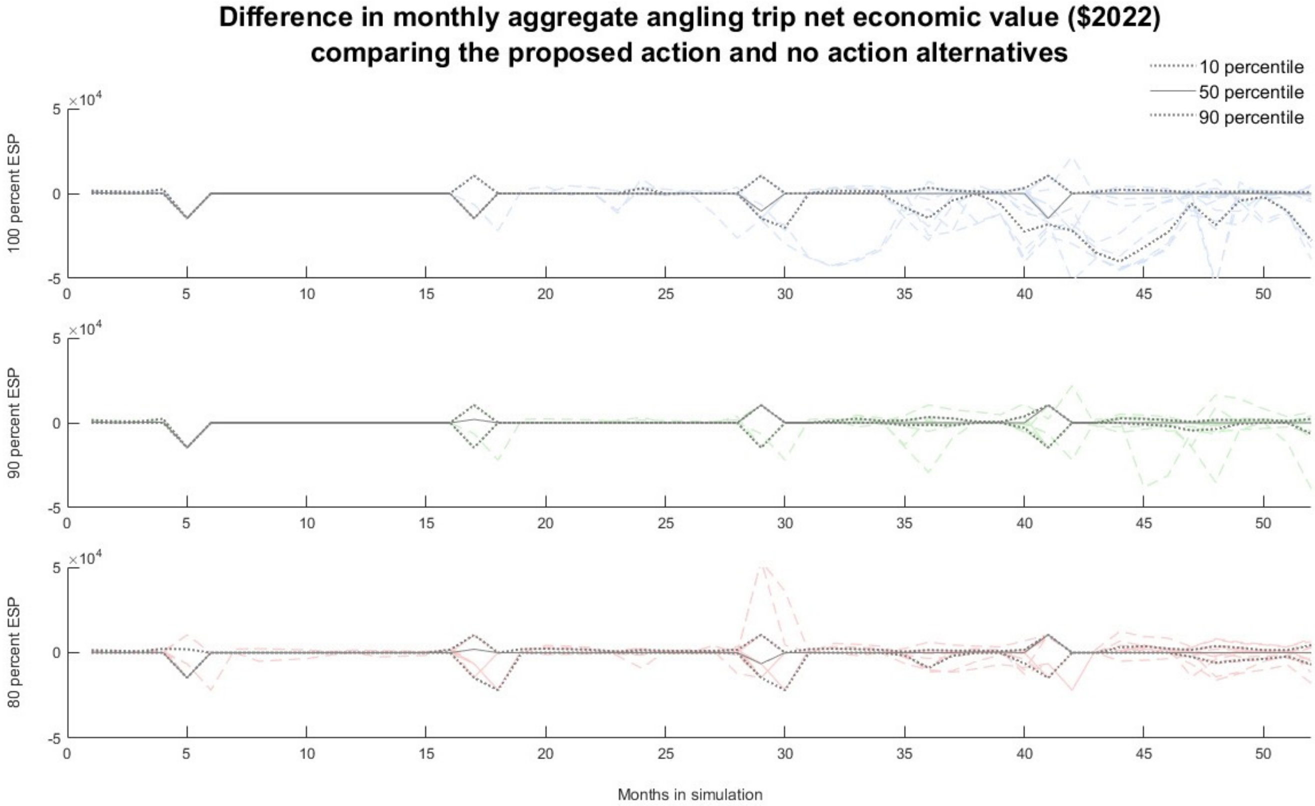

Figure 6.1. Difference in monthly aggregate angling trip net economic value comparing the proposed action and the No Action Alternatives in the Interim Guidelines SEIS. The 10th, 50th and 90th percentiles are reported for the 100% ESP scenario (top panel), 90% ESP scenario (middle panel) and 80% ESP scenario (bottom panel).

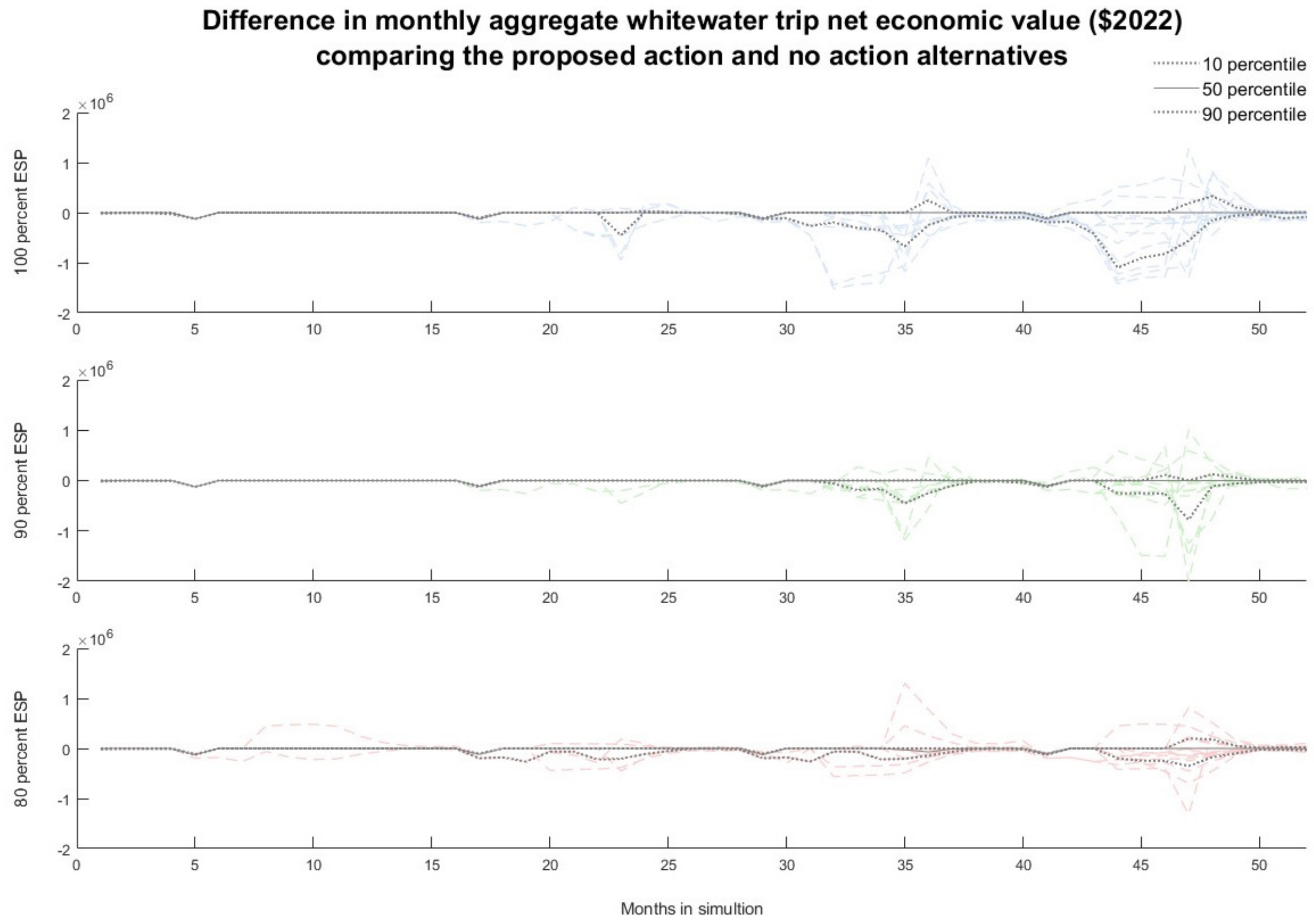

Figure 6.2. Difference in monthly aggregate whitewater trip net economic value comparing the proposed action and the No Action Alternatives in the Interim Guidelines SEIS. The 10th, 50th and 90th percentile are reported for the 100% ESP scenario (top panel), 90% ESP scenario (middle panel) and 80% ESP scenario (bottom panel).

Data Availability Statement:

Data generated during this study are published and available (Bair, 2024).

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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VII. Modeling Impacts of Different Reservoir Management Scenarios on Riparian Plant Communities and Vegetation Resources

BRADLEY BUTTERFIELD, NORTHERN ARIZONA UNIVERSITY, EMILY PALMQUIST, U.S. GEOLOGICAL SURVEY

Background and Methods

Native riparian vegetation is a key aspect of functioning riparian ecosystems. Riparian plant communities increase regional biodiversity (Sabo and others, 2005), harbor unique and culturally important species (Roberts and others, 1995; Fairley, 2005), support wildlife communities (Holmes and others, 2005; Ralston, 2005), alter sediment fluvial and aeolian sediment transport (Butterfield and others, 2020; Sankey and others, 2023), and provide shade and wind breaks for recreationists (Stewart and others, 2003). Along the Colorado River downstream from Glen Canyon Dam (GCD), expansion of woody riparian species has reduced already limited camping area (Hadley and others, 2018; Hazel and others, 2022).

The Long-term Experimental and Management Plan (LTEMP) goal for riparian plant communities is to support riparian vegetation that is diverse and primarily composed of native species (U.S. Department of Interior, 2016). While not included in the riparian vegetation goal, concerns over further reduction of camping areas due to plant encroachment is undesirable, so total cover of vegetation is a key consideration in this ecosystem (U.S. Department of Interior, 2016).

Under current dam operations, native plant species richness and cover are greater than nonnative species richness and cover, but woody plant encroachment continues (Durning and others, 2021; Palmquist and others, 2023).

Riparian plant communities are structured by both river flow patterns and air temperature (Tabbachi and others, 1998; Palmquist and others, 2018a; Butterfield and others, 2018). Across broad regions, air temperature determines which floristic groups occur along a river (Tabbachi and others, 1998; Palmquist and others, 2018a). Within climate gradients, the magnitude, timing, duration, and frequency of high and low flow patterns determines which plant species establish and grow (Poff and others, 1997). Air temperature, humidity, and precipitation can mediate plant water needs and thus plant responses to flow patterns, resulting in interactive effects between climate and flow patterns on riparian plant responses (Butterfield and others, 2018; Butterfield and others, 2023; Moran and others, 2023).

Along the Colorado River ecosystem (CRe), a steep temperature gradient of approximately 5 °C drives broader floristic patterns.

Four distinct floristic groups occur longitudinally and are associated with Glen Canyon (River Mile [RM] -15.5 – 0), Marble Canyon (RM 0-61), eastern Grand Canyon (RM 61-160), and western Grand Canyon (RM 160-240) (Palmquist and others, 2018a; Palmquist and others, 2023).

Within those floristic groups, plant communities are structured by hydrological zones related to dam operations (Palmquist and others, 2023). Communities differ among the areas inundated by daily river fluctuations (inundated by flows up to 25,000 cubic feet per second [cfs]), High Flow Experiments (HFEs, between 25,000 and 45,000 cfs), and exceptional and rare releases over 45,000 cfs (Palmquist and others, 2023). There are indications that the hotter temperatures of eastern and western Grand Canyon modify preferred hydrological conditions for some plant species, particularly on large sandbars (Butterfield and others, 2018). The prevalence of native species in this system is related to the timing of both high and low flow periods, where high flows during the summer maximize native plant richness and low flows in the winter are associated with greater proportions of native species relative to nonnative species (Butterfield and others, 2023). Thus, air temperature, the minimum discharge of the daily fluctuations during the lowest streamflow period, the peak discharge of daily fluctuations during the highest streamflow period, and the maximum discharge of the year (larger for HFE years) are key variables shaping riparian plant communities in the CRe.

Species and Training Data

To estimate the predicted response of riparian plant communities to operational alternatives, we conducted hydrological niche modeling of 47 common riparian plant species (33 native, 14 nonnative) growing on sandbars in the CRe (Table 7-1; Butterfield and Palmquist, 2024). The modeling methods were the same for the Interim Guidelines SEIS and LTEMP SEIS but differed in the modifications to the dam operations (see Chapter I) and resolution of the hydrological traces used (described below). The general framework for these analyses was developed in Butterfield and others (2018) and Kasprak and others (2021). Habitat suitability was estimated for the No Action scenario and all alternatives under consideration using Maximum Entropy (Maxent) algorithms (Phillips and others, 2006). Riparian plant community data from 44 long-term monitoring sandbar sites collected in 2014-2019 (Palmquist and others, 2018b; Palmquist and others, 2022), coupled with the digital elevation models (DEMs) of those sandbars (Grams and others, 2020), were used to train the models. These sandbars are all between Lees Ferry, AZ and the confluence of the Colorado River and Diamond Creek, AZ and represent a somewhat different plant community than is supported by other geomorphic types (Hazel and others, 2022; Palmquist and others, 2023).

The plant communities represented by these analyses, then, are the floristic communities of Marble Canyon, eastern Grand Canyon, and western Grand Canyon on large sandbars of considerable recreational and ecological value (Hazel and others, 2022; Palmquist and others, 2022; Palmquist and others, 2023). Models and results were developed for each floristic region independently.

Table 7-1. List of species used for hydrological niche modeling.

Scientific Name	Common Name	Native Status	Habit
Achnatherum hymenoides	Indian ricegrass	Native	Graminoid
Achnatherum speciosum	desert needlegrass	Native	Graminoid
Alhagi maurorum	camelthorn	Nonnative	Shrub
Aristida arizonica	Arizona threeawn	Native	Graminoid
Artemisia ludoviciana	white sagebrush	Native	Forb
Baccharis emoryi	Emory's baccharis	Native	Shrub
Baccharis salicifolia	mule-fat	Native	Shrub
Baccharis sarothroides	desertbroom	Native	Shrub
Bothriochloa barbinodis	cane bluestem	Native	Graminoid
Bouteloua barbata	sixweeks grama	Native	Graminoid
Brickellia longifolia	Longleaf brickellbush	Native	Shrub
Bromus diandrus	ripgut brome	Nonnative	Graminoid
Bromus rubens	red brome	Nonnative	Graminoid
Bromus tectorum	cheatgrass	Nonnative	Graminoid
Chloracantha spinosa	spiny chloracantha	Native	Forb
Conyza canadensis	Canadian horseweed	Nonnative	Forb
Cynodon dactylon	Bermudagrass	Nonnative	Graminoid
Datura wrightii	sacred thorn-apple	Native	Forb
Dicoria canescens	desert twinbugs	Native	Forb
Dieteria canescens	hoary tansyaster	Native	Forb
Equisetum arvense	field horsetail	Native	Forb
Eragrostis curvula	weeping lovegrass	Nonnative	Graminoid
Euthamia occidentalis	western goldentop	Native	Forb

Fallugia paradoxa	Apache plume	Native	Shrub
Gutierrezia sarothrae	broom snakeweed	Native	Shrub
Isocoma acradenia	alkali goldenbush	Native	Shrub
Juncus articulatus	jointleaf rush	Native	Graminoid
Lepidium fremontii	desert pepperweed	Native	Shrub
Melilotus officinalis	sweetclover	Nonnative	Forb
Muhlenbergia asperifolia	scratchgrass	Native	Graminoid
Phragmites australis	common reed	Native	Graminoid
Piptatherum miliaceum	smilograss	Nonnative	Graminoid
Pluchea sericea	arrowweed	Native	Shrub
Polypogon viridis	beardless rabbitsfoot grass	Nonnative	Graminoid
Prosopis glandulosa	honey mesquite	Native	Tree
Salix exigua	coyote willow	Native	Shrub
Salsola tragus	prickly Russian thistle	Nonnative	Forb
Schedonorus arundinaceus	tall fescue	Nonnative	Graminoid
Schismus arabicus	Arabian schismus	Nonnative	Graminoid
Schoenoplectus pungens	common threesquare	Native	Graminoid
Senegalia greggii	catclaw acacia	Native	Tree
Sporobolus contractus	spike dropseed	Native	Graminoid
Sporobolus cryptandrus	sand dropseed	Native	Graminoid
Sporobolus flexuosus	mesa dropseed	Native	Graminoid
Sporobolus gigantea	giant dropseed	Native	Graminoid
Stephanomeria pauciflora	brownplume wirelettuce	Native	Shrub
Tamarix sp.	salt cedar	Nonnative	Tree

Environmental Variables

Three hydrological variables, minimum temperature of the coldest month (January), mean annual precipitation, and solar insolation, were used as predictor variables in the habitat suitability models for each plant species.

Approximately 1km resolution average climate data were acquired from WorldClim version 2 (Fick and Hijmans, 2017). This resolution is too coarse to account for the steep elevation gradients within the CRe and therefore produce inaccurate climate estimates along the Colorado River. Temperature exhibits a strong, linear dependence on elevation, so we used the 10m USGS National Elevation Database (NED; Gesch and others, 2018) to statistically downscale air temperature. Precipitation is less dependent on elevation but exhibits strong spatial autocorrelation (Caster and Sankey, 2016; Palmquist and others, 2018a); thus, we used a spatial smoothing function to downscale precipitation (‘fields’ package, Nychka and others, 2021). The 10m NED was also used to estimate insolation using the ‘terra’ package in R (R Core Team, 2022; Hijmans, 2023).

For the Interim Guidelines SEIS, monthly traces provided by Reclamation (see Chapter I), including multiple traces with 80%, 90% and 100% of the ensemble streamflow predictions (ESPs), were used. These data were downscaled to 15-minute resolution by assuming maximum daily fluctuations by month outlined in LTEMP (U.S Department of Interior, 2016). The No Action Alternative was modeled without HFEs. The Proposed Action Alternative scenario was modeled two ways, one without HFEs and one with a 96 hour, ~40,000 cfs HFE. For the LTEMP SEIS, 30 hourly traces were used to represent each hydrological scenario (see Chapter II).

For both the Interim Guidelines SEIS and the LTEMP SEIS modeling, the elevation of each plant community monitoring plot above river stage was calculated at 15-minute intervals during the year prior to data collection. These elevations were used as estimates of depth to groundwater and inundation experienced by the plants in those plots. The hydrological variables were extracted from the distribution of elevations above river stage: the 95th percentile, 5th percentile, and minimum elevation. These variables reflect the trough of daily fluctuations during the lowest streamflow month of the year, the peak of daily fluctuations during the highest streamflow month of the year, and the peak of the HFE.

Model Predictions

The Maxent models for each species were spatially projected onto each sandbar using the 2019 DEMs and each of the traces under all scenarios. The results of the alternative flow scenarios were compared against the No Action scenario, such that results indicate changes in suitable habitat relative to No Action.

For each trace, the habitat suitability maps for each species were compared between the No Action and alternative scenarios to identify the amount of predicted habitat for each species that (1) switched from suitable to unsuitable or (2) switched from unsuitable to suitable, and identified the original amount of suitable habitat.

Habitat suitability thresholds varied among species and optimized the balance between errors of omission and commission based on metrics of model fit (Butterfield and others, 2023). These data were used to quantify the change in predicted habitat suitability between the No Action and alternative scenarios.

Rather than elaborating on predicted responses for all species, regions, and traces, we focused on three metrics of interest to stakeholders: species richness, proportion of vegetation cover that is native, and total vegetation cover. Analyses were subdivided into groups of traces with similar lake elevations: 0-10%; 10-25%; 25-50%; and 50-100%.

Both the absolute changes in habitat (m^2) and relative changes (%) are provided for context. Since the 44 long-term monitoring sandbars are a subset of sandbars in the CRe, we scaled up the absolute changes in habitat from the 44 long-term monitoring sandbar sites to the total estimated area changed. Total vegetated area in 2024 estimated from the models for the 44 monitoring sites (196,384 m^2) was approximately one order of magnitude smaller than the total vegetated sandbar area estimated from remote sensing (~1,400,000 – 2,300,000 m^2, depending on the definition of the riparian zone) by Durning and others (2021). Thus, all area estimates presented here are multiplied by 10 as an approximate attempt to scale up to sandbars across the entire river system. This is still an underestimate, given that sandbars only make up approximately 1/3 of the riparian zone in the CRe (Durning and others, 2021).

Model Limitations

This modeling approach can address shifts in the highest flows and lowest flows (for example, no HFEs versus having HFEs), but does not account for flow frequency or timing. Thus, changes in plant species habitat suitability due to alterations in the frequency, timing, or duration of HFEs would not be reflected by these analyses.

Plant composition and trends differ on sandbars relative to other geomorphic surfaces (like debris fans), so these analyses represent changes to a subset of the plant communities in the CRe (Palmquist and others, 2023).

These model results are for changes in habitat suitability, not plant occurrence or cover. Loss of habitat suitability can result in plant death but gain of habitat suitability does not guarantee plant colonization and growth. Further, we present absolute changes in habitat suitability, but this does not account for the location of that habitat.

For example, an equivalent amount of suitable habitat may be available in both scenarios, but that suitable habitat may not be located in the same place. If this were to happen in reality, plant death would occur in the newly unsuitable habitat and there may or may not be recolonization in the newly suitable habitat.

Results of Analyzing Interim Guideline SEIS Alternatives

The probabilities of HFEs under the No Action and Alternative three scenarios are nearly identical (see Chapter III). Thus, we compared No Action to the Action Alternative without HFEs, and No Action to Action Alternative with HFEs. Either with or without HFEs, the small differences in monthly volumes between No Action and Action Alternative had little to no effect on the hydrological variables that we have demonstrated as driving habitat suitability for riparian plant species (Butterfield and others, 2018). Thus, the majority of traces resulted in zero predicted difference in vegetation metrics between the No Action and Action Alternative scenarios, either with or without HFEs (Tables 7-2 through 7-4). The largest predicted effect of Action Alternative was a 1.7% change in proportion of native cover in one region of the CRe, and the largest effects were observed under the driest 10% of traces. Overall, the predicted effects of the Action Alternative versus No Action on riparian vegetation metrics are negligible. Model results are available in Butterfield and Palmquist (2024).

Table 7-2. Predicted net change in the proportion of vegetation native cover for the Interim Guidelines SEIS, calculated as the difference between cumulative habitat gains and losses comparing the Action Alternative to the No Action scenario, with or without HFEs, across all sandbars and years 2025-2027. Suitable habitat totals under the No Action scenario in 2024 were used to calculate the relative (%) change values. Different trace classes represent lowest (0-10%) to highest (50-100%) lake level quantiles. Marble Canyon – RM 0-61, Eastern Grand Canyon – RM 61-160, Western Grand Canyon – RM 160-226.

No HFE		Predicted Value in 2024 (Proportion)			Predicted Change					
					Absolute (Proportion)			Relative (%)		
Region	Traces	Mean	95% CI		Mean	95% CI		Mean	95% CI	
Marble Canyon	50-100%	0.79	0.78	0.80	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	0.79	0.78	0.80	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	0.79	0.78	0.79	0.00	-0.01	0.00	-0.6	-0.8	-0.4
	0-10%	0.79	0.78	0.79	-0.01	-0.01	0.00	-0.8	-1.0	-0.6
Eastern Grand Canyon	50-100%	0.73	0.71	0.74	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	0.73	0.71	0.74	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	0.73	0.72	0.74	0.00	0.00	0.00	0.0	-0.1	0.1
	0-10%	0.73	0.72	0.73	0.00	0.00	0.00	-0.1	-0.2	0.0
Western Grand Canyon	50-100%	0.64	0.62	0.67	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	0.64	0.62	0.67	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	0.64	0.63	0.66	0.00	0.00	0.00	-0.3	-0.5	0.0
	0-10%	0.64	0.63	0.65	0.00	0.00	0.00	-0.1	-0.4	0.1

With HFE		Predicted Value in 2024 (Proportion)			Predicted Change					
					Absolute (Proportion)			Relative (%)		
Region	Traces	Mean	95% CI		Mean	95% CI		Mean	95% CI	
Marble Canyon	50-100%	0.68	0.67	0.69	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	0.68	0.67	0.69	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	0.68	0.68	0.69	0.00	-0.01	0.00	-0.7	-0.9	-0.5
	0-10%	0.68	0.68	0.69	0.00	-0.01	0.00	-0.6	-0.8	-0.5
Eastern Grand Canyon	50-100%	0.58	0.56	0.60	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	0.58	0.56	0.60	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	0.58	0.57	0.59	0.00	0.00	0.01	0.6	0.3	1.0
	0-10%	0.58	0.57	0.59	0.00	0.00	0.01	0.8	0.5	1.1
Western Grand Canyon	50-100%	0.47	0.46	0.47	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	0.47	0.46	0.47	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	0.47	0.46	0.47	0.00	0.00	0.00	0.4	-0.1	0.9
	0-10%	0.47	0.46	0.47	0.00	0.00	0.01	1.0	0.4	1.7

Table 7-3. Predicted net change in vegetation species richness for the Interim Guidelines SEIS, calculated as the difference between species gains and losses comparing the Action Alternative to the No Action scenario, with or without HFEs, across all sandbars and years 2025-2027. Suitable habitat totals under the No Action scenario in 2024 were used to calculate the relative (%) change values. Different trace classes represent lowest (0-10%) to highest (50-100%) lake level quantiles. Marble Canyon – RM 0-61, Eastern Grand Canyon – RM 61-160, Western Grand Canyon – RM 160-226.

No HFE		Predicted Value in 2024 (Species per Sandbar)			Predicted Change					
					Absolute (Species)			Relative (%)		
Region	Traces	Mean	95% CI		Mean	95% CI		Mean	95% CI	
Marble Canyon	50-100%	34.68	33.77	35.60	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	34.68	33.77	35.60	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	34.68	34.10	35.27	0.05	-0.01	0.10	0.1	0.0	0.3
	0-10%	34.68	34.29	35.08	-0.04	-0.09	0.01	-0.1	-0.3	0.0
Eastern Grand Canyon	50-100%	31.69	31.10	32.29	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	31.69	31.10	32.29	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	31.69	31.31	32.07	-0.02	-0.11	0.07	-0.1	-0.4	0.2
	0-10%	31.69	31.44	31.95	-0.14	-0.22	-0.05	-0.4	-0.7	-0.1
Western Grand Canyon	50-100%	21.38	19.98	22.77	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	21.38	19.98	22.77	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	21.38	20.50	22.25	0.07	-0.02	0.16	0.3	-0.1	0.8
	0-10%	21.38	20.79	21.96	-0.02	-0.09	0.06	-0.1	-0.4	0.3

With HFE		Predicted Value in 2024 (Species per Sandbar)			Predicted Change					
					Absolute (Species)			Relative (%)		
Region	Traces	Mean	95% CI		Mean	95% CI		Mean	95% CI	
Marble Canyon	50-100%	32.58	32.14	33.02	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	32.58	32.14	33.02	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	32.58	32.29	32.86	0.05	-0.01	0.11	0.2	0.0	0.3
	0-10%	32.58	32.38	32.77	0.03	-0.01	0.07	0.1	0.0	0.2
Eastern Grand Canyon	50-100%	30.54	29.93	31.15	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	30.54	29.93	31.15	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	30.54	30.14	30.93	-0.08	-0.15	-0.01	-0.3	-0.5	0.0
	0-10%	30.54	30.27	30.81	-0.13	-0.19	-0.06	-0.4	-0.6	-0.2
Western Grand Canyon	50-100%	21.13	20.29	21.96	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	21.13	20.29	21.96	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	21.13	20.59	21.66	0.08	-0.04	0.21	0.4	-0.2	1.0
	0-10%	21.13	20.76	21.49	0.05	-0.02	0.11	0.2	-0.1	0.5

Table 7-4. Predicted net change in suitable habitat for vegetation for the Interim Guidelines SEIS, calculated as the difference between cumulative habitat gains and losses comparing the Action Alternative to the No Action scenario, with or without HFEs, across all sandbars and years 2025-2027. Suitable habitat totals under the No Action scenario in 2024 were used to calculate the relative (%) change values. Different trace classes represent lowest (0-10%) to highest (50-100%) lake level quantiles. Marble Canyon – RM 0-61, Eastern Grand Canyon – RM 61-160, Western Grand Canyon – RM 160-226.

No HFE		Predicted Value in 2024 $(10^5 m^2)$			Predicted Change					
					Absolute $(10^3 m^2)$			Relative (%)		
Region	Traces	Mean	95% CI		Mean	95% CI		Mean	95% CI	
Marble Canyon	50-100%	11.27	8.77	13.77	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	11.27	8.77	13.77	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	11.27	9.66	12.87	-1.84	-5.61	1.92	-0.2	-0.5	0.2
	0-10%	11.27	10.18	12.36	-5.22	-8.83	-1.61	-0.5	-0.8	-0.1
Eastern Grand Canyon	50-100%	6.03	4.41	7.64	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	6.03	4.41	7.64	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	6.03	5.00	7.06	-0.79	-3.07	1.50	-0.1	-0.5	0.2
	0-10%	6.03	5.33	6.72	-2.90	-5.30	-0.50	-0.5	-0.9	-0.1
Western Grand Canyon	50-100%	5.70	4.19	7.21	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	5.70	4.19	7.21	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	5.70	4.76	6.65	-0.95	-3.41	1.52	-0.2	-0.6	0.3
	0-10%	5.70	5.07	6.34	-3.05	-6.49	0.39	-0.5	-1.1	0.1

With HFE		Predicted Value in 2024 $(10^5 m^2)$			Predicted Change					
					Absolute $(10^3 m^2)$			Relative (%)		
Region	Traces	Mean	95% CI		Mean	95% CI		Mean	95% CI	
Marble Canyon	50-100%	9.35	8.18	10.53	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	9.35	8.18	10.53	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	9.35	8.59	10.12	1.97	0.08	3.87	0.2	0.0	0.4
	0-10%	9.35	8.83	9.87	0.95	-0.61	2.50	0.1	-0.1	0.3
Eastern Grand Canyon	50-100%	5.37	4.45	6.28	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	5.37	4.45	6.28	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	5.37	4.77	5.96	-0.14	-1.35	1.08	0.0	-0.3	0.2
	0-10%	5.37	4.96	5.77	-1.13	-2.59	0.34	-0.2	-0.5	0.1
Western Grand Canyon	50-100%	4.91	4.15	5.66	0.00	0.00	0.00	0.0	0.0	0.0
	25-50%	4.91	4.15	5.66	0.00	0.00	0.00	0.0	0.0	0.0
	10-25%	4.91	4.42	5.39	-1.84	-4.85	1.18	-0.4	-1.0	0.2
	0-10%	4.91	4.57	5.24	-2.43	-4.65	-0.21	-0.5	-0.9	0.0

Results of Analyzing LTEMP SEIS Alternatives

The only alternative that resulted in substantial differences in plant community habitat suitability when compared to the No Action scenario was the Non-Bypass Alternative. While results varied quantitatively among regions of the CRe, and among traces, overall the proportion of native-to-non-native cover increased (Figure 7-1, Table 7-5), species richness increased (Figure 7-2, Table 7-6), and total vegetation cover decreased (Figure 7-3, Table 7-7) relative to the No Action scenario.

Impacts of the other LTEMP SEIS alternatives (those including bypass options) on vegetation resources did not differ significantly from the No Action Alternative, with nearly all changes below 1%. This is due to the minor changes in monthly and HFE volumes associated with these alternatives. Model results are available in Butterfield and Palmquist (2024).

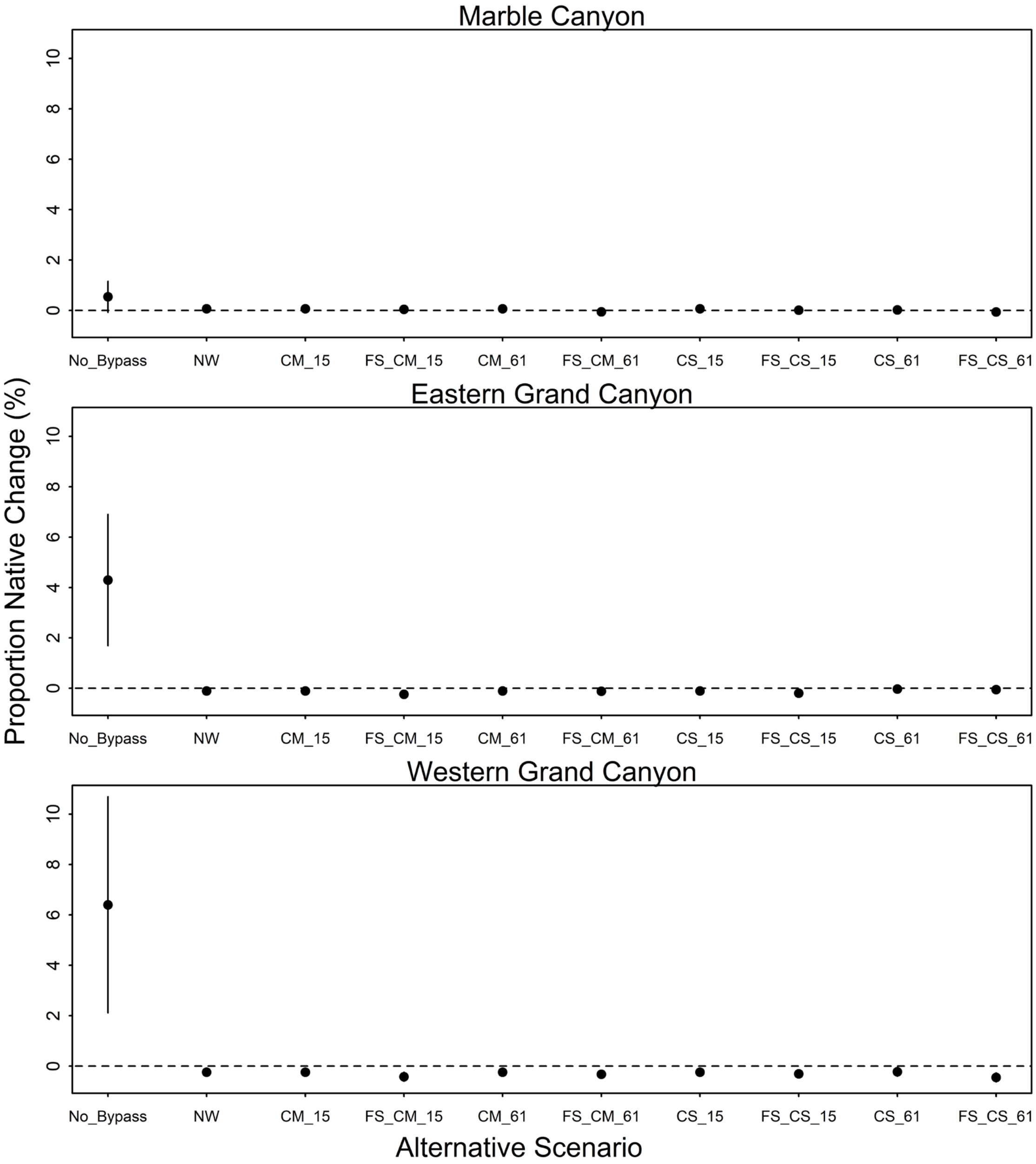

Figure 7-1. Predicted net change in proportion native cover, calculated as the difference between cumulative habitat gains and losses comparing each alternative to the No Action scenario, represented as percent change. Marble Canyon – RM 0-61, Eastern Grand Canyon – RM 61-160, Western Grand Canyon – RM 160-226. Acronyms are: NW – new sediment accounting window, CM_15 – cool mix targeting RM 15, FS_CM_15 – cool mix with flow spike targeting RM 15, CM_61 – cool mix targeting RM 61, the confluence with Little Colorado River, FS_CM_61 – cool mix with flow spike targeting RM 61, CS_15 – cold shock targeting RM 15, FS_CS_15 – cold shock with flow spikes targeting RM 15, CS_61 – cold shock targeting RM 61, FS_CS_61 – cold shock with flow spikes targeting RM 61.

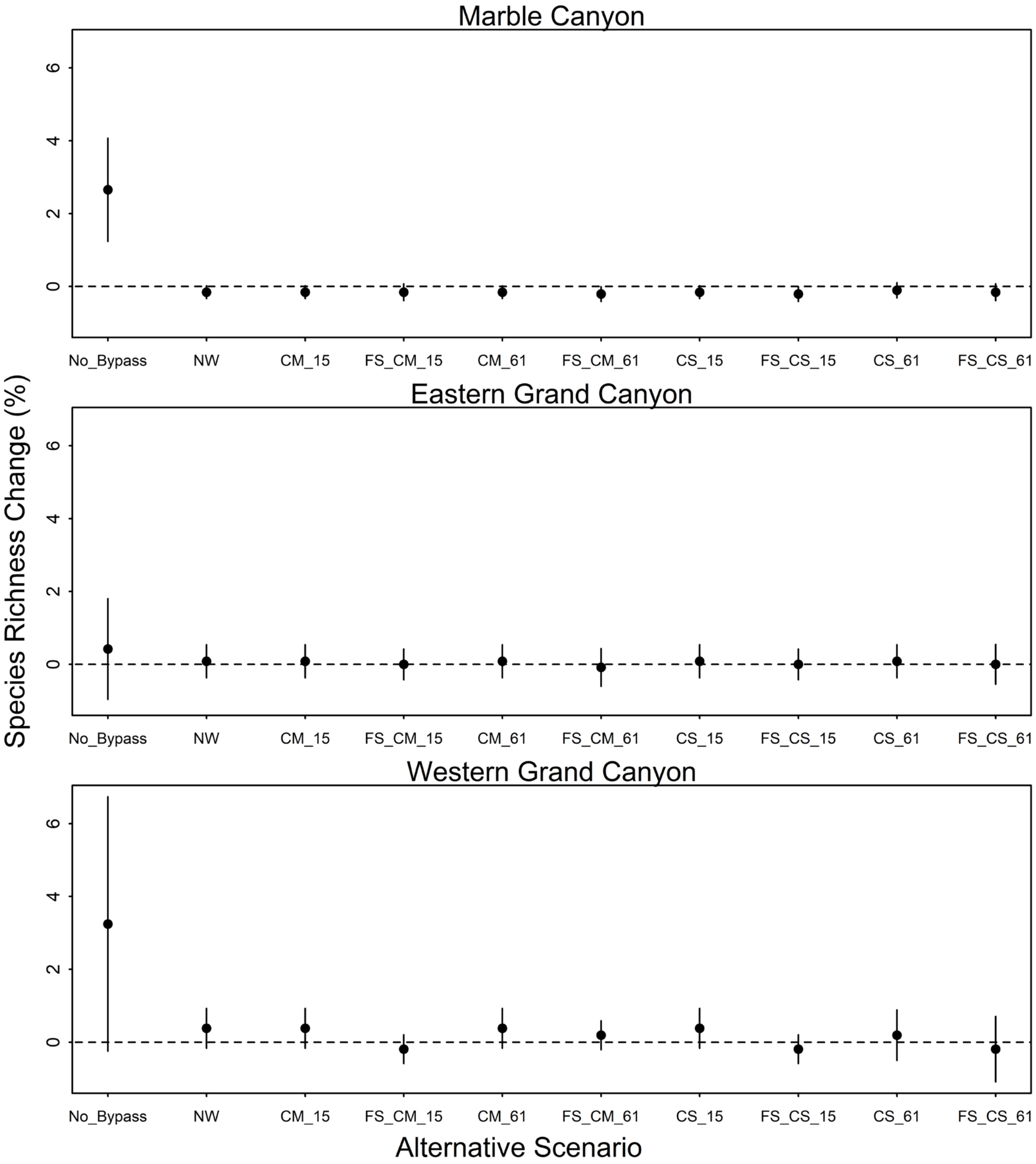

Figure 7-2. Predicted net change in species richness, calculated as the difference between cumulative habitat gains and losses comparing each alternative to the No Action scenario, represented as percent change. Marble Canyon – RM 0-61, Eastern Grand Canyon – RM 61-160, Western Grand Canyon – RM 160-226. Acronyms are: NW – new sediment accounting window, CM_15 – cool mix targeting RM 15, FS_CM_15 – cool mix with flow spike targeting RM 15, CM_61 – cool mix targeting RM 61, the confluence with Little Colorado River, FS_CM_61 – cool mix with flow spike targeting RM 61, CS_15 – cold shock targeting RM 15, FS_CS_15 – cold shock with flow spikes targeting RM 15, CS_61 – cold shock targeting RM 61, FS_CS_61 – cold shock with flow spikes targeting RM 61.

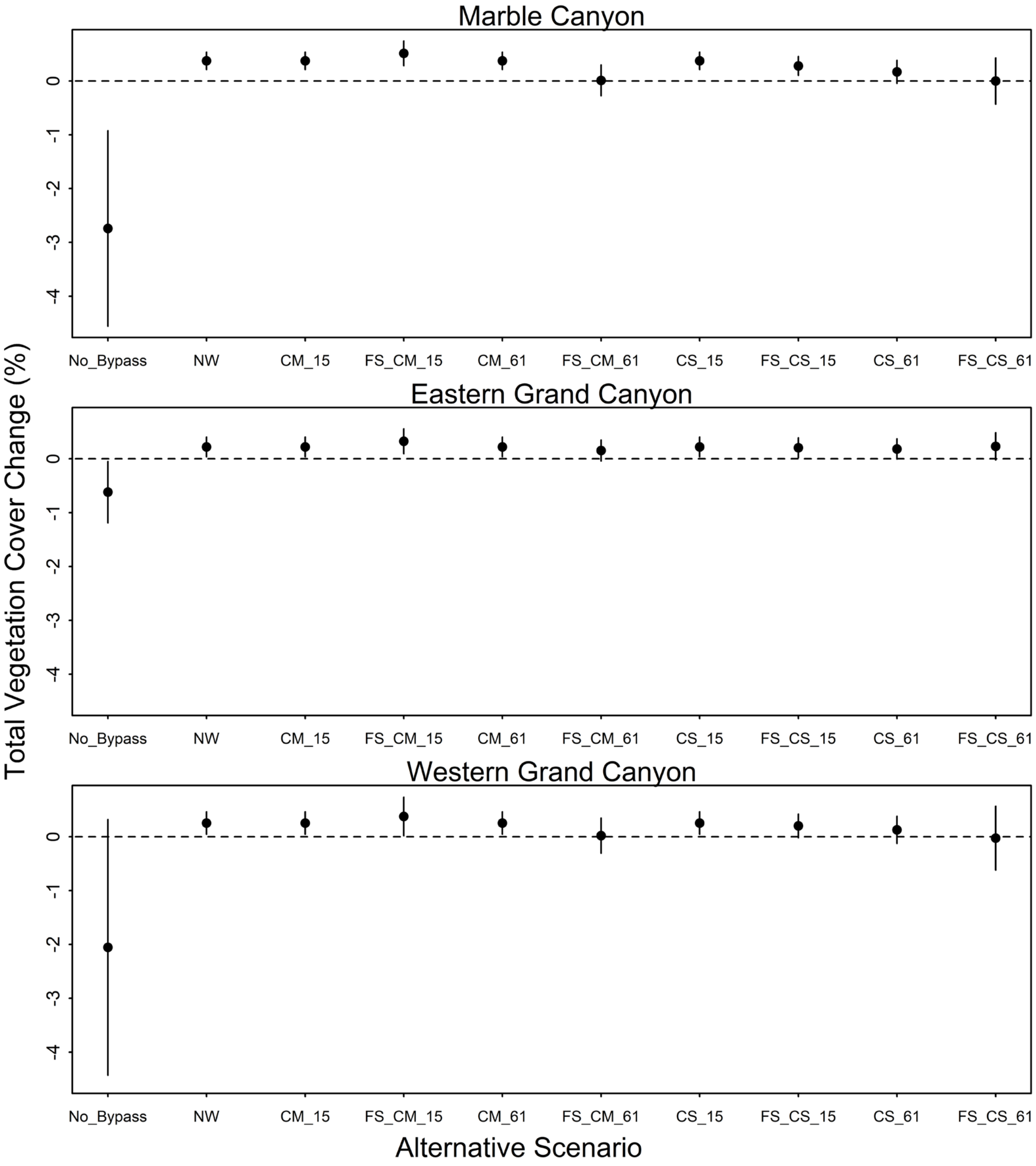

Figure 7-3. Predicted net change in total vegetation cover, calculated as the difference between cumulative habitat gains and losses comparing each alternative to the No Action scenario, represented as percent change. Marble Canyon – RM 0-61, Eastern Grand Canyon – RM 61-160, Western Grand Canyon – RM 160-226. Acronyms are: NW – new sediment accounting window, CM_15 – cool mix targeting RM 15, FS_CM_15 – cool mix with flow spike targeting RM 15, CM_61 – cool mix targeting RM 61, the confluence with Little Colorado River, FS_CM_61 – cool mix with flow spike targeting RM 61, CS_15 – cold shock targeting RM 15, FS_CS_15 – cold shock with flow spikes targeting RM 15, CS_61 – cold shock targeting RM 61, FS_CS_61 – cold shock with flow spikes targeting RM 61

Table 7-5. Predicted net change in the proportion of vegetation native cover for the LTEMP SEIS, calculated as the difference between cumulative habitat gains and losses comparing each alternative to the No Action scenario, across all sandbars and years 2025-2027. Suitable habitat totals under the No Action scenario in 2024 were used to calculate the relative (%) change values. Different trace classes represent lowest (0-10%) to highest (50-100%) lake level quantiles. Marble Canyon – RM 0-61, Eastern Grand Canyon – RM 61-160, Western Grand Canyon – RM 160-226. Acronyms are: CM_15 – cool mix targeting RM 15, CM_61 – cool mix targeting RM 61, the confluence with Little Colorado River, CS_15 – cold shock targeting RM 15, CS_61 – cold shock targeting RM 61, FS_CM_15 – cool mix with flow spike targeting RM 15, FS_CM_61 – cool mix with flow spike targeting RM 61, FS_CS_15 – cold shock with flow spikes targeting RM 15, FS_CS_61 – cold shock with flow spikes targeting RM 61, New Accounting Window – new sediment accounting window.

			No Action (proportion)			Absolute Change (proportion)			Relative Change (%)		
Alternative	Region	Traces	Mean	95% CI		Mean	95% CI		Mean	95% CI	
CM_15	Marble Canyon	0-10%	0.67	0.66	0.69	0.000	0.000	0.001	0.06	0.02	0.11
		10-25%	0.67	0.66	0.68	0.002	0.001	0.002	0.23	0.11	0.36
		25-50%	0.66	0.66	0.67	0.002	0.001	0.002	0.23	0.12	0.33
		50-100%	0.67	0.66	0.68	0.001	0.000	0.001	0.08	0.05	0.11
	Eastern Grand Canyon	0-10%	0.61	0.59	0.64	-0.001	-0.001	0.000	-0.11	-0.18	-0.03
		10-25%	0.61	0.60	0.63	0.003	0.001	0.004	0.42	0.17	0.66
		25-50%	0.65	0.63	0.66	0.003	0.001	0.004	0.41	0.15	0.67
		50-100%	0.63	0.62	0.64	0.001	0.001	0.001	0.17	0.10	0.23
	Western Grand Canyon	0-10%	0.49	0.47	0.51	-0.001	-0.002	0.000	-0.24	-0.40	-0.08
		10-25%	0.49	0.48	0.50	0.003	0.000	0.005	0.51	0.02	1.00
		25-50%	0.55	0.53	0.58	0.002	0.000	0.004	0.44	0.08	0.81
		50-100%	0.53	0.51	0.54	0.001	0.000	0.002	0.16	0.04	0.29
CM_61	Marble Canyon	0-10%	0.67	0.66	0.69	0.000	0.000	0.001	0.06	0.02	0.11
		10-25%	0.67	0.66	0.68	0.002	0.001	0.002	0.23	0.11	0.35
		25-50%	0.66	0.66	0.67	0.001	0.001	0.002	0.21	0.11	0.31
		50-100%	0.67	0.66	0.68	0.000	0.000	0.001	0.06	0.03	0.09
	Eastern Grand Canyon	0-10%	0.61	0.59	0.64	-0.001	-0.001	0.000	-0.11	-0.18	-0.03
		10-25%	0.61	0.60	0.63	0.003	0.001	0.004	0.44	0.20	0.69
		25-50%	0.65	0.63	0.66	0.003	0.001	0.005	0.43	0.16	0.70
		50-100%	0.63	0.62	0.64	0.001	0.001	0.002	0.21	0.14	0.29
	Western Grand Canyon	0-10%	0.49	0.47	0.51	-0.001	-0.002	0.000	-0.24	-0.40	-0.08
		10-25%	0.49	0.48	0.50	0.003	0.000	0.005	0.53	0.04	1.01
		25-50%	0.55	0.53	0.58	0.003	0.001	0.005	0.48	0.09	0.87

		50-100%	0.53	0.51	0.54	0.001	0.000	0.002	0.21	0.07	0.34
CS_15	Marble Canyon	0-10%	0.67	0.66	0.69	0.000	0.000	0.001	0.06	0.02	0.11
		10-25%	0.67	0.66	0.68	0.002	0.001	0.002	0.24	0.12	0.36
		25-50%	0.66	0.66	0.67	0.002	0.001	0.002	0.26	0.14	0.37
		50-100%	0.67	0.66	0.68	0.001	0.000	0.001	0.08	0.05	0.11
	Eastern Grand Canyon	0-10%	0.61	0.59	0.64	-0.001	-0.001	0.000	-0.11	-0.18	-0.03
		10-25%	0.61	0.60	0.63	0.002	0.001	0.004	0.37	0.12	0.62
		25-50%	0.65	0.63	0.66	0.002	0.001	0.003	0.32	0.11	0.52
		50-100%	0.63	0.62	0.64	0.001	0.000	0.001	0.13	0.07	0.18
	Western Grand Canyon	0-10%	0.49	0.47	0.51	-0.001	-0.002	0.000	-0.24	-0.40	-0.08
		10-25%	0.49	0.48	0.50	0.002	0.000	0.005	0.49	0.00	0.98
		25-50%	0.55	0.53	0.58	0.002	0.000	0.003	0.32	0.03	0.60
		50-100%	0.53	0.51	0.54	0.001	0.000	0.001	0.13	0.01	0.25
CS_61	Marble Canyon	0-10%	0.67	0.66	0.69	0.000	0.000	0.000	0.02	-0.03	0.07
		10-25%	0.67	0.66	0.68	0.001	0.000	0.002	0.19	0.06	0.31
		25-50%	0.66	0.66	0.67	0.002	0.001	0.002	0.26	0.14	0.37
		50-100%	0.67	0.66	0.68	0.000	0.000	0.001	0.07	0.05	0.10
	Eastern Grand Canyon	0-10%	0.61	0.59	0.64	0.000	-0.001	0.001	-0.03	-0.15	0.09
		10-25%	0.61	0.60	0.63	0.003	0.001	0.004	0.43	0.17	0.68
		25-50%	0.65	0.63	0.66	0.002	0.001	0.003	0.31	0.11	0.51
		50-100%	0.63	0.62	0.64	0.001	0.001	0.001	0.14	0.08	0.20
	Western Grand Canyon	0-10%	0.49	0.47	0.51	-0.001	-0.002	0.000	-0.23	-0.40	-0.05
		10-25%	0.49	0.48	0.50	0.002	0.000	0.005	0.49	-0.01	0.99
		25-50%	0.55	0.53	0.58	0.002	0.000	0.003	0.31	0.03	0.59
		50-100%	0.53	0.51	0.54	0.001	0.000	0.001	0.13	0.01	0.25
FS_CM_15	Marble Canyon	0-10%	0.67	0.66	0.69	0.000	0.000	0.001	0.04	-0.02	0.10
		10-25%	0.67	0.66	0.68	0.002	0.001	0.003	0.26	0.15	0.38
		25-50%	0.66	0.66	0.67	-0.001	-0.001	0.000	-0.08	-0.16	-0.01
		50-100%	0.67	0.66	0.68	0.000	0.000	0.001	0.07	0.03	0.10
	Eastern Grand Canyon	0-10%	0.61	0.59	0.64	-0.001	-0.002	-0.001	-0.24	-0.30	-0.17
		10-25%	0.61	0.60	0.63	0.002	0.001	0.004	0.37	0.12	0.61
		25-50%	0.65	0.63	0.66	0.000	0.000	0.000	0.00	-0.06	0.06
		50-100%	0.63	0.62	0.64	0.001	0.000	0.001	0.10	0.05	0.15
	Western Grand	0-10%	0.49	0.47	0.51	-0.002	-0.003	-0.001	-0.42	-0.60	-0.24
		10-25%	0.49	0.48	0.50	0.002	0.000	0.004	0.40	-0.09	0.90

	Canyon	25-50%	0.55	0.53	0.58	0.000	-0.001	0.001	-0.04	-0.18	0.10
		50-100%	0.53	0.51	0.54	0.000	0.000	0.001	0.07	-0.04	0.19
FS_CM_61	Marble Canyon	0-10%	0.67	0.66	0.69	0.000	-0.001	0.000	-0.06	-0.13	0.01
		10-25%	0.67	0.66	0.68	0.000	0.000	0.000	-0.01	-0.06	0.04
		25-50%	0.66	0.66	0.67	-0.001	-0.001	0.000	-0.08	-0.14	-0.01
		50-100%	0.67	0.66	0.68	0.000	-0.001	0.000	-0.06	-0.11	-0.01
	Eastern Grand Canyon	0-10%	0.61	0.59	0.64	-0.001	-0.001	0.000	-0.12	-0.20	-0.03
		10-25%	0.61	0.60	0.63	0.000	0.000	0.001	0.01	-0.08	0.10
		25-50%	0.65	0.63	0.66	0.000	0.000	0.000	0.01	-0.04	0.06
		50-100%	0.63	0.62	0.64	0.000	0.000	0.001	0.07	-0.01	0.15
	Western Grand Canyon	0-10%	0.49	0.47	0.51	-0.002	-0.002	-0.001	-0.32	-0.46	-0.18
		10-25%	0.49	0.48	0.50	0.000	-0.001	0.000	-0.09	-0.27	0.08
		25-50%	0.55	0.53	0.58	0.000	-0.001	0.001	-0.01	-0.12	0.10
		50-100%	0.53	0.51	0.54	0.000	-0.001	0.001	-0.02	-0.19	0.16
FS_CS_15	Marble Canyon	0-10%	0.67	0.66	0.69	0.000	0.000	0.000	0.01	-0.04	0.06
		10-25%	0.67	0.66	0.68	0.002	0.001	0.002	0.24	0.12	0.36
		25-50%	0.66	0.66	0.67	0.000	-0.001	0.000	-0.05	-0.09	-0.01
		50-100%	0.67	0.66	0.68	0.000	0.000	0.000	0.04	0.01	0.07
	Eastern Grand Canyon	0-10%	0.61	0.59	0.64	-0.001	-0.002	-0.001	-0.19	-0.25	-0.14
		10-25%	0.61	0.60	0.63	0.002	0.001	0.004	0.37	0.12	0.62
		25-50%	0.65	0.63	0.66	0.000	-0.001	0.000	-0.07	-0.10	-0.03
		50-100%	0.63	0.62	0.64	0.001	0.000	0.001	0.10	0.04	0.17
	Western Grand Canyon	0-10%	0.49	0.47	0.51	-0.002	-0.002	-0.001	-0.31	-0.45	-0.17
		10-25%	0.49	0.48	0.50	0.002	0.000	0.005	0.49	0.00	0.98
		25-50%	0.55	0.53	0.58	-0.001	-0.001	0.000	-0.13	-0.21	-0.04
		50-100%	0.53	0.51	0.54	0.000	0.000	0.001	0.09	-0.03	0.21
FS_CS_61	Marble Canyon	0-10%	0.67	0.66	0.69	0.000	-0.001	0.000	-0.06	-0.16	0.03
		10-25%	0.67	0.66	0.68	0.000	-0.001	0.000	-0.07	-0.13	0.00
		25-50%	0.66	0.66	0.67	0.000	-0.001	0.000	-0.04	-0.08	0.00
		50-100%	0.67	0.66	0.68	0.000	0.000	0.000	-0.02	-0.06	0.03
	Eastern Grand Canyon	0-10%	0.61	0.59	0.64	0.000	-0.001	0.001	-0.05	-0.21	0.10
		10-25%	0.61	0.60	0.63	0.000	-0.001	0.000	-0.02	-0.12	0.07
		25-50%	0.65	0.63	0.66	-0.001	-0.001	0.000	-0.09	-0.13	-0.05
		50-100%	0.63	0.62	0.64	0.000	-0.001	0.000	-0.02	-0.10	0.06
	Western	0-10%	0.49	0.47	0.51	-0.002	-0.003	-0.001	-0.45	-0.62	-0.27

	Grand Canyon	10-25%	0.49	0.48	0.50	-0.001	-0.002	0.000	-0.27	-0.49	-0.05
		25-50%	0.55	0.53	0.58	-0.001	-0.001	0.000	-0.16	-0.25	-0.07
		50-100%	0.53	0.51	0.54	-0.001	-0.002	0.000	-0.12	-0.29	0.05
New Accounting Window	Marble Canyon	0-10%	0.67	0.66	0.69	0.000	0.000	0.001	0.06	0.02	0.11
		10-25%	0.67	0.66	0.68	0.002	0.001	0.002	0.24	0.12	0.36
		25-50%	0.66	0.66	0.67	0.002	0.001	0.003	0.27	0.15	0.39
		50-100%	0.67	0.66	0.68	0.001	0.000	0.001	0.09	0.06	0.12
	Eastern Grand Canyon	0-10%	0.61	0.59	0.64	-0.001	-0.001	0.000	-0.11	-0.18	-0.03
		10-25%	0.61	0.60	0.63	0.002	0.001	0.004	0.37	0.12	0.62
		25-50%	0.65	0.63	0.66	0.002	0.001	0.003	0.32	0.12	0.53
		50-100%	0.63	0.62	0.64	0.001	0.000	0.001	0.12	0.07	0.17
	Western Grand Canyon	0-10%	0.49	0.47	0.51	-0.001	-0.002	0.000	-0.24	-0.40	-0.08
		10-25%	0.49	0.48	0.50	0.002	0.000	0.005	0.49	0.00	0.98
		25-50%	0.55	0.53	0.58	0.002	0.000	0.003	0.34	0.04	0.63
		50-100%	0.53	0.51	0.54	0.001	0.000	0.001	0.13	0.01	0.25

Table 7-6. Predicted net change in vegetation species richness for the LTEMP SEIS, calculated as the difference between cumulative habitat gains and losses comparing each alternative to the No Action scenario, across all sandbars and years 2025-2027. Suitable habitat totals under the No Action scenario in 2024 were used to calculate the relative (%) change values. Different trace classes represent lowest (0-10%) to highest (50-100%) lake level quantiles. Marble Canyon – RM 0-61, Eastern Grand Canyon – RM 61-160, Western Grand Canyon – RM 160-226. Acronyms are: CM_15 – cool mix targeting RM 15, CM_61 – cool mix targeting RM 61, the confluence with Little Colorado River, CS_15 – cold shock targeting RM 15, CS_61 – cold shock targeting RM 61, FS_CM_15 – cool mix with flow spike targeting RM 15, FS_CM_61 – cool mix with flow spike targeting RM 61, FS_CS_15 – cold shock with flow spikes targeting RM 15, FS_CS_61 – cold shock with flow spikes targeting RM 61, New Accounting Window – new sediment accounting window.

			No Action			Absolute Change			Relative Change		
			(species per sandbar)			(species per sandbar)			(%)		
Alternative	Region	Traces	Mean	95% CI		Mean	95% CI		Mean	95% CI	
CM_15	Marble Canyon	0-10%	33.70	32.87	34.53	-0.05	-0.11	0.01	-0.16	-0.33	0.02
		10-25%	33.59	32.95	34.23	0.11	0.00	0.21	0.31	0.00	0.63
		25-50%	33.18	32.56	33.80	0.09	0.01	0.17	0.27	0.03	0.51
		50-100%	33.52	33.11	33.93	0.05	0.02	0.08	0.15	0.06	0.24
	Eastern Grand Canyon	0-10%	30.49	29.36	31.61	0.03	-0.11	0.16	0.08	-0.37	0.54
		10-25%	30.43	29.55	31.31	0.12	-0.02	0.27	0.40	-0.06	0.87
		25-50%	29.60	28.69	30.52	0.08	-0.02	0.18	0.26	-0.08	0.60
		50-100%	29.85	29.28	30.41	0.08	0.02	0.15	0.27	0.06	0.49
	Western Grand Canyon	0-10%	21.83	20.07	23.59	0.08	-0.04	0.20	0.38	-0.16	0.93
		10-25%	21.70	20.32	23.08	0.05	-0.11	0.21	0.23	-0.51	0.97
		25-50%	21.04	19.93	22.15	0.13	0.01	0.24	0.59	0.05	1.14
		50-100%	21.36	20.60	22.11	0.00	-0.06	0.06	0.00	-0.27	0.27
CM_61	Marble Canyon	0-10%	33.70	32.87	34.53	-0.05	-0.11	0.01	-0.16	-0.33	0.02
		10-25%	33.59	32.95	34.23	0.12	0.01	0.22	0.34	0.03	0.66
		25-50%	33.18	32.56	33.80	0.10	0.01	0.18	0.29	0.04	0.55
		50-100%	33.52	33.11	33.93	0.05	0.02	0.08	0.16	0.06	0.25
	Eastern Grand	0-10%	30.49	29.36	31.61	0.03	-0.11	0.16	0.08	-0.37	0.54
		10-25%	30.43	29.55	31.31	0.14	-0.01	0.28	0.46	-0.02	0.93

	Canyon	25-50%	29.60	28.69	30.52	0.07	-0.03	0.16	0.22	-0.09	0.53
		50-100%	29.85	29.28	30.41	0.09	0.02	0.15	0.29	0.07	0.51
	Western	0-10%	21.83	20.07	23.59	0.08	-0.04	0.20	0.38	-0.16	0.93
	Grand	10-25%	21.70	20.32	23.08	0.05	-0.11	0.21	0.23	-0.51	0.97
	Canyon	25-50%	21.04	19.93	22.15	0.11	-0.01	0.23	0.51	-0.07	1.09
		50-100%	21.36	20.60	22.11	-0.01	-0.07	0.06	-0.04	-0.34	0.26
CS_15	Marble	0-10%	33.70	32.87	34.53	-0.05	-0.11	0.01	-0.16	-0.33	0.02
	Canyon	10-25%	33.59	32.95	34.23	0.12	0.01	0.22	0.34	0.04	0.65
		25-50%	33.18	32.56	33.80	0.08	0.01	0.15	0.25	0.04	0.46
		50-100%	33.52	33.11	33.93	0.05	0.02	0.07	0.14	0.05	0.22
	Eastern	0-10%	30.49	29.36	31.61	0.03	-0.11	0.16	0.08	-0.37	0.54
	Grand	10-25%	30.43	29.55	31.31	0.12	-0.02	0.27	0.40	-0.06	0.87
	Canyon	25-50%	29.60	28.69	30.52	0.10	0.00	0.20	0.33	0.00	0.67
		50-100%	29.85	29.28	30.41	0.08	0.02	0.15	0.27	0.06	0.49
	Western	0-10%	21.83	20.07	23.59	0.08	-0.04	0.20	0.38	-0.16	0.93
	Grand	10-25%	21.70	20.32	23.08	0.08	-0.08	0.23	0.35	-0.35	1.04
	Canyon	25-50%	21.04	19.93	22.15	0.13	0.02	0.23	0.59	0.10	1.08
		50-100%	21.36	20.60	22.11	0.00	-0.05	0.05	0.00	-0.22	0.22
CS_61	Marble	0-10%	33.70	32.87	34.53	-0.04	-0.11	0.04	-0.10	-0.31	0.10
	Canyon	10-25%	33.59	32.95	34.23	0.11	0.00	0.21	0.31	0.00	0.63
		25-50%	33.18	32.56	33.80	0.08	0.01	0.15	0.25	0.04	0.46
		50-100%	33.52	33.11	33.93	0.05	0.02	0.08	0.15	0.07	0.23
	Eastern	0-10%	30.49	29.36	31.61	0.03	-0.11	0.16	0.08	-0.37	0.54
	Grand	10-25%	30.43	29.55	31.31	0.11	-0.04	0.25	0.35	-0.13	0.83
	Canyon	25-50%	29.60	28.69	30.52	0.08	-0.01	0.16	0.26	-0.02	0.54
		50-100%	29.85	29.28	30.41	0.08	0.02	0.15	0.27	0.06	0.49
	Western	0-10%	21.83	20.07	23.59	0.04	-0.11	0.19	0.19	-0.50	0.88
	Grand	10-25%	21.70	20.32	23.08	0.03	-0.13	0.18	0.12	-0.59	0.82
	Canyon	25-50%	21.04	19.93	22.15	0.13	0.02	0.23	0.59	0.10	1.08
		50-100%	21.36	20.60	22.11	0.00	-0.05	0.05	0.00	-0.25	0.25

FS_CM_15	Marble	0-10%	33.70	32.87	34.53	-0.05	-0.13	0.03	-0.16	-0.39	0.08
	Canyon	10-25%	33.59	32.95	34.23	0.12	0.01	0.22	0.34	0.03	0.66
		25-50%	33.18	32.56	33.80	-0.01	-0.06	0.04	-0.02	-0.17	0.13
		50-100%	33.52	33.11	33.93	0.04	0.02	0.07	0.13	0.05	0.20
	Eastern	0-10%	30.49	29.36	31.61	0.00	-0.13	0.13	0.00	-0.42	0.42
	Grand	10-25%	30.43	29.55	31.31	0.14	-0.01	0.29	0.46	-0.04	0.95
	Canyon	25-50%	29.60	28.69	30.52	0.00	-0.07	0.07	0.00	-0.23	0.23
		50-100%	29.85	29.28	30.41	0.08	0.01	0.14	0.26	0.05	0.47
	Western	0-10%	21.83	20.07	23.59	-0.04	-0.13	0.04	-0.19	-0.59	0.20
	Grand	10-25%	21.70	20.32	23.08	0.10	-0.06	0.26	0.46	-0.27	1.19
	Canyon	25-50%	21.04	19.93	22.15	0.02	-0.08	0.11	0.08	-0.37	0.54
		50-100%	21.36	20.60	22.11	0.00	-0.04	0.04	0.00	-0.19	0.19
FS_CM_61	Marble	0-10%	33.70	32.87	34.53	-0.07	-0.14	0.00	-0.21	-0.41	-0.01
	Canyon	10-25%	33.59	32.95	34.23	-0.02	-0.07	0.03	-0.06	-0.22	0.09
		25-50%	33.18	32.56	33.80	-0.02	-0.06	0.02	-0.07	-0.19	0.05
		50-100%	33.52	33.11	33.93	0.01	-0.02	0.05	0.04	-0.07	0.15
	Eastern	0-10%	30.49	29.36	31.61	-0.03	-0.18	0.13	-0.08	-0.60	0.43
	Grand	10-25%	30.43	29.55	31.31	0.00	-0.09	0.09	0.00	-0.29	0.29
	Canyon	25-50%	29.60	28.69	30.52	-0.01	-0.05	0.03	-0.04	-0.17	0.09
		50-100%	29.85	29.28	30.41	0.01	-0.07	0.09	0.03	-0.24	0.31
	Western	0-10%	21.83	20.07	23.59	0.04	-0.04	0.13	0.19	-0.20	0.59
	Grand	10-25%	21.70	20.32	23.08	0.05	-0.05	0.15	0.23	-0.24	0.70
	Canyon	25-50%	21.04	19.93	22.15	0.04	-0.05	0.12	0.17	-0.25	0.59
		50-100%	21.36	20.60	22.11	0.00	-0.07	0.07	0.00	-0.35	0.35
FS_CS_15	Marble	0-10%	33.70	32.87	34.53	-0.07	-0.14	0.00	-0.21	-0.41	-0.01
	Canyon	10-25%	33.59	32.95	34.23	0.12	0.01	0.22	0.34	0.04	0.65
		25-50%	33.18	32.56	33.80	-0.02	-0.06	0.01	-0.07	-0.17	0.03
		50-100%	33.52	33.11	33.93	0.02	-0.01	0.05	0.06	-0.02	0.15
	Eastern	0-10%	30.49	29.36	31.61	0.00	-0.13	0.13	0.00	-0.42	0.42
	Grand	10-25%	30.43	29.55	31.31	0.12	-0.02	0.27	0.40	-0.06	0.87

	Canyon	25-50%	29.60	28.69	30.52	-0.02	-0.05	0.01	-0.07	-0.18	0.03
		50-100%	29.85	29.28	30.41	0.07	0.00	0.13	0.22	0.01	0.44
	Western Grand Canyon	0-10%	21.83	20.07	23.59	-0.04	-0.13	0.04	-0.19	-0.59	0.20
		10-25%	21.70	20.32	23.08	0.08	-0.08	0.23	0.35	-0.35	1.04
		25-50%	21.04	19.93	22.15	0.02	-0.02	0.05	0.08	-0.09	0.26
		50-100%	21.36	20.60	22.11	-0.01	-0.06	0.05	-0.04	-0.30	0.22
FS_CS_61	Marble Canyon	0-10%	33.70	32.87	34.53	-0.05	-0.13	0.03	-0.16	-0.39	0.08
		10-25%	33.59	32.95	34.23	-0.02	-0.08	0.04	-0.06	-0.24	0.11
		25-50%	33.18	32.56	33.80	-0.02	-0.07	0.02	-0.07	-0.20	0.07
		50-100%	33.52	33.11	33.93	-0.01	-0.05	0.02	-0.04	-0.15	0.07
	Eastern Grand Canyon	0-10%	30.49	29.36	31.61	0.00	-0.17	0.17	0.00	-0.55	0.55
		10-25%	30.43	29.55	31.31	-0.03	-0.12	0.06	-0.10	-0.39	0.19
		25-50%	29.60	28.69	30.52	0.00	-0.05	0.05	0.00	-0.18	0.18
		50-100%	29.85	29.28	30.41	0.03	-0.06	0.11	0.09	-0.20	0.37
	Western Grand Canyon	0-10%	21.83	20.07	23.59	-0.04	-0.24	0.15	-0.19	-1.09	0.71
		10-25%	21.70	20.32	23.08	0.03	-0.09	0.14	0.12	-0.41	0.64
		25-50%	21.04	19.93	22.15	0.02	-0.02	0.05	0.08	-0.09	0.26
		50-100%	21.36	20.60	22.11	0.01	-0.05	0.06	0.04	-0.22	0.30
New Accounting Window	Marble Canyon	0-10%	33.70	32.87	34.53	-0.05	-0.11	0.01	-0.16	-0.33	0.02
		10-25%	33.59	32.95	34.23	0.12	0.01	0.22	0.34	0.04	0.65
		25-50%	33.18	32.56	33.80	0.08	0.01	0.15	0.25	0.04	0.46
		50-100%	33.52	33.11	33.93	0.05	0.02	0.08	0.15	0.06	0.23
	Eastern Grand Canyon	0-10%	30.49	29.36	31.61	0.03	-0.11	0.16	0.08	-0.37	0.54
		10-25%	30.43	29.55	31.31	0.12	-0.02	0.27	0.40	-0.06	0.87
		25-50%	29.60	28.69	30.52	0.09	0.00	0.18	0.30	-0.01	0.61
		50-100%	29.85	29.28	30.41	0.07	0.01	0.14	0.24	0.03	0.45
	Western Grand Canyon	0-10%	21.83	20.07	23.59	0.08	-0.04	0.20	0.38	-0.16	0.93
		10-25%	21.70	20.32	23.08	0.08	-0.08	0.23	0.35	-0.35	1.04
		25-50%	21.04	19.93	22.15	0.13	0.02	0.23	0.59	0.10	1.08
		50-100%	21.36	20.60	22.11	-0.01	-0.05	0.04	-0.04	-0.24	0.17

Table 7-7. Predicted net change in total vegetation cover for the LTEMP SEIS, calculated as the difference between cumulative habitat gains and losses comparing each alternative to the No Action scenario, across all sandbars and years 2025-2027. Suitable habitat totals under the No Action scenario in 2024 were used to calculate the relative (%) change values. Different trace classes represent lowest (0-10%) to highest (50-100%) lake level quantiles. Marble Canyon – RM 0-61, Eastern Grand Canyon – RM 61-160, Western Grand Canyon – RM 160-226. Acronyms are: CM_15 – cool mix targeting RM 15, CM_61 – cool mix targeting RM 61, the confluence with Little Colorado River, CS_15 – cold shock targeting RM 15, CS_61 – cold shock targeting RM 61, FS_CM_15 – cool mix with flow spike targeting RM 15, FS_CM_61 – cool mix with flow spike targeting RM 61, FS_CS_15 – cold shock with flow spikes targeting RM 15, FS_CS_61 – cold shock with flow spikes targeting RM 61, New Accounting Window – new sediment accounting window.

			No Action (10^4 m^2)			Absolute Change (10^4 m^2)			Relative Change (%)		
Alternative	Region	Traces	Mean	95% CI		Mean	95% CI		Mean	95% CI	
CM_15	Marble Canyon	0-10%	28.64	19.40	37.87	0.11	0.06	0.15	0.37	0.21	0.53
		10-25%	28.16	21.16	35.16	0.14	0.04	0.24	0.51	0.15	0.87
		25-50%	19.12	14.19	24.06	0.09	0.05	0.12	0.45	0.26	0.64
		50-100%	23.66	19.98	27.35	0.03	0.00	0.06	0.12	0.02	0.23
	Eastern Grand Canyon	0-10%	29.52	18.45	40.60	0.07	0.01	0.12	0.22	0.04	0.40
		10-25%	29.43	21.00	37.87	0.09	0.01	0.16	0.30	0.04	0.55
		25-50%	22.38	15.89	28.87	0.04	0.01	0.07	0.18	0.06	0.29
		50-100%	25.88	21.30	30.46	0.03	0.00	0.05	0.10	0.02	0.19
	Western Grand Canyon	0-10%	27.32	17.71	36.94	0.07	0.01	0.13	0.25	0.05	0.46
		10-25%	27.01	19.91	34.11	0.10	-0.03	0.23	0.38	-0.10	0.86
		25-50%	19.71	14.39	25.02	0.06	0.03	0.10	0.33	0.14	0.51
		50-100%	23.49	19.61	27.37	0.02	-0.01	0.05	0.08	-0.06	0.22
CM_61	Marble Canyon	0-10%	28.64	19.40	37.87	0.11	0.06	0.15	0.37	0.21	0.53
		10-25%	28.16	21.16	35.16	0.12	0.01	0.23	0.43	0.05	0.80
		25-50%	19.12	14.19	24.06	0.06	0.03	0.09	0.30	0.16	0.44
		50-100%	23.66	19.98	27.35	-0.02	-0.05	0.02	-0.07	-0.22	0.08
	Eastern Grand Canyon	0-10%	29.52	18.45	40.60	0.07	0.01	0.12	0.22	0.04	0.40
		10-25%	29.43	21.00	37.87	0.08	0.00	0.16	0.27	0.01	0.53
		25-50%	22.38	15.89	28.87	0.03	0.01	0.06	0.14	0.02	0.26

		50-100%	25.88	21.30	30.46	0.02	-0.01	0.04	0.06	-0.03	0.16
	Western Grand Canyon	0-10%	27.32	17.71	36.94	0.07	0.01	0.13	0.25	0.05	0.46
		10-25%	27.01	19.91	34.11	0.08	-0.06	0.22	0.30	-0.22	0.82
		25-50%	19.71	14.39	25.02	0.05	0.02	0.08	0.26	0.11	0.42
		50-100%	23.49	19.61	27.37	-0.02	-0.07	0.03	-0.08	-0.28	0.13
CS_15	Marble Canyon	0-10%	28.64	19.40	37.87	0.11	0.06	0.15	0.37	0.21	0.53
		10-25%	28.16	21.16	35.16	0.19	0.09	0.28	0.66	0.33	1.00
		25-50%	19.12	14.19	24.06	0.19	0.09	0.28	0.97	0.48	1.47
		50-100%	23.66	19.98	27.35	0.07	0.04	0.09	0.28	0.17	0.39
	Eastern Grand Canyon	0-10%	29.52	18.45	40.60	0.07	0.01	0.12	0.22	0.04	0.40
		10-25%	29.43	21.00	37.87	0.10	0.02	0.17	0.33	0.08	0.58
		25-50%	22.38	15.89	28.87	0.06	0.03	0.09	0.28	0.14	0.42
		50-100%	25.88	21.30	30.46	0.03	0.01	0.06	0.13	0.05	0.22
	Western Grand Canyon	0-10%	27.32	17.71	36.94	0.07	0.01	0.13	0.25	0.05	0.46
		10-25%	27.01	19.91	34.11	0.14	0.02	0.26	0.51	0.06	0.96
		25-50%	19.71	14.39	25.02	0.13	0.04	0.22	0.66	0.20	1.12
		50-100%	23.49	19.61	27.37	0.05	0.02	0.08	0.20	0.07	0.34
CS_61	Marble Canyon	0-10%	28.64	19.40	37.87	0.05	-0.01	0.11	0.17	-0.04	0.38
		10-25%	28.16	21.16	35.16	0.13	0.05	0.22	0.47	0.16	0.77
		25-50%	19.12	14.19	24.06	0.19	0.09	0.28	0.98	0.48	1.49
		50-100%	23.66	19.98	27.35	0.06	0.03	0.08	0.24	0.14	0.34
	Eastern Grand Canyon	0-10%	29.52	18.45	40.60	0.05	0.00	0.11	0.18	0.00	0.37
		10-25%	29.43	21.00	37.87	0.08	0.01	0.15	0.28	0.03	0.52
		25-50%	22.38	15.89	28.87	0.06	0.03	0.09	0.28	0.14	0.42
		50-100%	25.88	21.30	30.46	0.03	0.01	0.05	0.12	0.04	0.21
	Western Grand Canyon	0-10%	27.32	17.71	36.94	0.04	-0.03	0.10	0.13	-0.12	0.38
		10-25%	27.01	19.91	34.11	0.09	-0.02	0.20	0.34	-0.06	0.73
		25-50%	19.71	14.39	25.02	0.13	0.04	0.22	0.67	0.20	1.13
		50-100%	23.49	19.61	27.37	0.04	0.01	0.07	0.17	0.05	0.29
FS_CM_15	Marble	0-10%	28.64	19.40	37.87	0.15	0.08	0.21	0.51	0.28	0.74

	Canyon	10-25%	28.16	21.16	35.16	0.20	0.10	0.31	0.72	0.34	1.10
		25-50%	19.12	14.19	24.06	-0.07	-0.18	0.04	-0.39	-0.96	0.19
		50-100%	23.66	19.98	27.35	0.03	-0.01	0.06	0.12	-0.03	0.26
	Eastern Grand Canyon	0-10%	29.52	18.45	40.60	0.10	0.03	0.16	0.33	0.10	0.56
		10-25%	29.43	21.00	37.87	0.12	0.04	0.19	0.40	0.15	0.66
		25-50%	22.38	15.89	28.87	0.00	-0.04	0.05	0.00	-0.20	0.21
		50-100%	25.88	21.30	30.46	0.03	0.00	0.05	0.11	0.01	0.21
	Western Grand Canyon	0-10%	27.32	17.71	36.94	0.10	0.01	0.20	0.38	0.02	0.73
		10-25%	27.01	19.91	34.11	0.16	0.02	0.29	0.57	0.08	1.07
		25-50%	19.71	14.39	25.02	-0.04	-0.16	0.08	-0.19	-0.80	0.41
		50-100%	23.49	19.61	27.37	0.02	-0.03	0.06	0.07	-0.13	0.27
FS_CM_61	Marble Canyon	0-10%	28.64	19.40	37.87	0.00	-0.08	0.08	0.01	-0.28	0.30
		10-25%	28.16	21.16	35.16	-0.06	-0.14	0.03	-0.20	-0.50	0.10
		25-50%	19.12	14.19	24.06	-0.09	-0.18	0.01	-0.46	-0.96	0.05
		50-100%	23.66	19.98	27.35	-0.09	-0.14	-0.03	-0.37	-0.61	-0.13
	Eastern Grand Canyon	0-10%	29.52	18.45	40.60	0.05	-0.01	0.10	0.15	-0.04	0.35
		10-25%	29.43	21.00	37.87	0.02	-0.06	0.09	0.05	-0.19	0.30
		25-50%	22.38	15.89	28.87	-0.01	-0.05	0.03	-0.05	-0.22	0.12
		50-100%	25.88	21.30	30.46	-0.01	-0.04	0.02	-0.04	-0.16	0.08
	Western Grand Canyon	0-10%	27.32	17.71	36.94	0.01	-0.08	0.09	0.02	-0.30	0.35
		10-25%	27.01	19.91	34.11	-0.07	-0.19	0.05	-0.26	-0.69	0.17
		25-50%	19.71	14.39	25.02	-0.06	-0.16	0.05	-0.28	-0.81	0.25
		50-100%	23.49	19.61	27.37	-0.07	-0.14	0.00	-0.28	-0.58	0.01
FS_CS_15	Marble Canyon	0-10%	28.64	19.40	37.87	0.08	0.03	0.13	0.28	0.11	0.45
		10-25%	28.16	21.16	35.16	0.18	0.09	0.28	0.66	0.32	0.99
		25-50%	19.12	14.19	24.06	0.02	-0.01	0.05	0.10	-0.07	0.26
		50-100%	23.66	19.98	27.35	0.03	0.01	0.06	0.14	0.03	0.25
	Eastern Grand Canyon	0-10%	29.52	18.45	40.60	0.06	0.01	0.12	0.21	0.02	0.39
		10-25%	29.43	21.00	37.87	0.10	0.02	0.17	0.33	0.08	0.58
		25-50%	22.38	15.89	28.87	0.02	0.00	0.05	0.10	-0.02	0.22

		50-100%	25.88	21.30	30.46	0.03	0.01	0.05	0.11	0.02	0.19
	Western Grand Canyon	0-10%	27.32	17.71	36.94	0.06	0.00	0.11	0.20	-0.02	0.42
		10-25%	27.01	19.91	34.11	0.14	0.02	0.26	0.50	0.06	0.95
		25-50%	19.71	14.39	25.02	0.01	-0.02	0.05	0.08	-0.12	0.27
		50-100%	23.49	19.61	27.37	0.02	-0.01	0.05	0.08	-0.05	0.22
FS_CS_61	Marble Canyon	0-10%	28.64	19.40	37.87	0.00	-0.12	0.12	0.00	-0.43	0.43
		10-25%	28.16	21.16	35.16	-0.02	-0.09	0.06	-0.06	-0.33	0.22
		25-50%	19.12	14.19	24.06	0.06	0.03	0.09	0.29	0.13	0.45
		50-100%	23.66	19.98	27.35	0.00	-0.03	0.04	0.01	-0.13	0.16
	Eastern Grand Canyon	0-10%	29.52	18.45	40.60	0.07	-0.01	0.14	0.23	-0.02	0.49
		10-25%	29.43	21.00	37.87	0.03	-0.04	0.10	0.10	-0.15	0.35
		25-50%	22.38	15.89	28.87	0.04	0.01	0.07	0.19	0.06	0.32
		50-100%	25.88	21.30	30.46	0.02	-0.01	0.04	0.07	-0.04	0.17
	Western Grand Canyon	0-10%	27.32	17.71	36.94	-0.01	-0.17	0.15	-0.03	-0.62	0.57
		10-25%	27.01	19.91	34.11	-0.02	-0.12	0.07	-0.09	-0.43	0.25
		25-50%	19.71	14.39	25.02	0.05	0.01	0.09	0.25	0.06	0.44
		50-100%	23.49	19.61	27.37	-0.01	-0.05	0.04	-0.03	-0.23	0.18
New Accounting Window	Marble Canyon	0-10%	28.64	19.40	37.87	0.11	0.06	0.15	0.37	0.21	0.53
		10-25%	28.16	21.16	35.16	0.18	0.09	0.28	0.65	0.31	0.98
		25-50%	19.12	14.19	24.06	0.17	0.08	0.26	0.90	0.44	1.35
		50-100%	23.66	19.98	27.35	0.07	0.04	0.09	0.29	0.19	0.40
	Eastern Grand Canyon	0-10%	29.52	18.45	40.60	0.07	0.01	0.12	0.22	0.04	0.40
		10-25%	29.43	21.00	37.87	0.10	0.02	0.17	0.33	0.08	0.58
		25-50%	22.38	15.89	28.87	0.06	0.03	0.09	0.26	0.13	0.39
		50-100%	25.88	21.30	30.46	0.03	0.01	0.06	0.13	0.05	0.22
	Western Grand Canyon	0-10%	27.32	17.71	36.94	0.07	0.01	0.13	0.25	0.05	0.46
		10-25%	27.01	19.91	34.11	0.13	0.01	0.26	0.50	0.05	0.95
		25-50%	19.71	14.39	25.02	0.12	0.04	0.21	0.62	0.19	1.04
		50-100%	23.49	19.61	27.37	0.05	0.02	0.08	0.21	0.08	0.34

Data Availability Statement:

Data generated during this study are published and available (Butterfield and Palmquist, 2024).

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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VIII. Modeling Impacts of Different Reservoir Management Scenarios on Dissolved Oxygen Concentrations in Glen Canyon Dam Releases

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Background and Methods

Metalimnion low dissolved oxygen (DO) zones can develop in reservoirs when large inflows (such as occur with floods) create an interflow (density current) from which oxygen is consumed faster than it is re-introduced from other water layers (Thornton and others, 1991). In Lake Powell, these metalimnion low DO zones develop each year, generally reaching their maximum development in September (Johnson and Page, 1981). Low oxygen is often most pronounced in the heads of side bays but is advected into the metalimnion (Johnson and Page, 1981). Ongoing analysis of historic profiles suggests that the magnitude of these low oxygen events increases when the reservoir inflow is low and spring snowmelt inflows are large (Deemer, 2023). These conditions can mobilize deltaic sediments, carrying limiting nutrients and organic carbon into the reservoir and promoting high rates of water column decomposition (Deemer, 2023). These low DO zones usually reach Glen Canyon Dam (GCD) in September or early October, although under lower water levels and large spring inflows such as were observed in 2023, low DO concentrations arrived at the forebay in July (DO below 5 mg/L persisted from 10 July to 3 November 2023, a total of 116 days; (U.S. Geological Survey, 2024)). A previous low DO event (in 2005) coincided with much lower recruitment and growth in the Lees Ferry Rainbow Trout fishery (Korman and others, 2012), so the low DO observed in Glen Canyon is of concern.

Low DO levels can pose both chronic and acute threats that are of concern to the Rainbow Trout fishery below GCD. Specifically, dissolved oxygen DO concentrations below 5.2 mg/L often have growth and reproductive effects for cold water fish and concentrations below 3.8 mg/L are estimated to cause ≥ 50% growth impairment and mark the onset of fish mortality events in rainbow trout (Saari and others, 2018). This document describes DO modeling that was conducted to estimate late summer and early fall dissolved oxygen concentrations in GCD releases under different management scenarios. We report the fraction of traces that are above or below the 5.2 mg/L DO threshold, which likely represents an upper end of concentrations that begin to be stressful for trout and aquatic invertebrates.

Modeling Methods and Results for the Interim Guidelines SEIS

We used a long-term record of DO profiles from the reservoir forebay (site name LPCR0024; Deemer and others, 2023; Andrews and Deemer, 2023) to model and predict DO concentration within a 10 m envelope of the penstock depth for 30 historical reconstructions of hydrology at either 80%, 90%, or 100% of ensemble streamflow prediction (ESP), for a total of 90 hydrological traces under each of two alternatives (No Action and Proposed Action), generated as part of the Interim Guidelines Supplemental Environmental Impact Statement (SEIS).

While the Lake Powell CE-QUAL-W2 does have a DO module (Williams, 2007), recent observations suggest the need for its recalibration to improve performance under low water levels and with the aging of the reservoir.

We used a total of 132 water quality profiles from the months of August, September, and October (1967-2022) to calculate annual mean late-summer/early fall DO concentrations in six 10-m layers of the Lake Powell water column that represent the depths from which water could be drawn through the penstocks under the various SEIS hydrological traces being examined here (6 to <16 m, 16 to <26 m, 26 to <36 m, 36 to <46 m, 46 to <56 m, and 56 to <66 m). Water quality profile data are available as part of a ScienceBase data release (Andrews and Deemer, 2023). We then built linear models to predict these water-layer-specific DO concentrations as a function of minimum spring reservoir elevation in that year, the volume of the spring inflow (calculated as the inflow from April-July), and the years since the reservoir was filled. Modeling was done using the "lm" function in R version 4.3.0 (R Core Team, 2019) and models of 10m depth bins had the structure: DO ~ Inflow + Minimum Elevation * Age. This model was based on the best model for predicting whole-metalimnion mean DO in the late summer and fall (Deemer, 2023). The models were then used to predict DO based on spring inflow volumes and minimum spring reservoir elevations in the hydrologic traces generated from each scenario. Predictions were made from the models in R using the predict.lm function in the stats package of base R (R Core Team, 2019).

In cases where the reservoir elevation was <3490 feet, we predicted a high-end 8 mg/L DO concentration would pass downstream. This assumption was based on the aeration that has been observed when water is spilled through the bypass tubes (Hueftle and Stevens, 2001; Vernieu, 2010). Bypass releases of 15,000 ft^3/s during the 2008 high flow experiment resulted in supersaturated DO concentrations (12.6 milligrams per liter [mg/L]; Vernieu, 2010) below the dam, so we consider 8 mg/L DO a conservative estimate for spills under lower lake elevations (with bypass spill rates of 14,620 cubic feet per second (cfs) at lake elevations of 3490 feet, and spill rates dropping at lower elevations).

Results of Analyzing Interim Guideline SEIS Alternatives

Across both the No Action and Proposed Action examined in this SEIS, 79% of the year by trace combinations are predicted to have mean DO concentrations <5 mg/L in the late summer and early fall (709 out of 900; Figure 8-1; Deemer and others, 2024). Tailwater low DO events (<5 mg/L) were only very slightly more probable under the Proposed Action Alternative (80% of years) than under the No Action Alternative (78% of years). Across both the No Action and Proposed Action Alternatives, reduced hydrological inputs had higher probabilities of low DO events (83% and 90% for No Action and Proposed Action 80% hydrology respectively) than traces with 100% of historical hydrology (72% and 70% for No Action and Proposed Action respectively). This may be due to the lower Lake Powell elevations that result from reduced hydrology (but that are not low enough to trigger bypass releases; Figure 8-2). Model outputs from this exercise are available in Deemer and others (2024).

Modeling Methods and Results for the LTEMP SEIS

Similar to the Interim Guidelines SEIS, we used a long-term record of DO profiles from the reservoir forebay (site name LPCR0024; Deemer and others, 2023) to model and predict DO concentration within a 10 m envelope of the penstock depth, this time for 300 traces generated as part of the LTEMP SEIS. None of the LTEMP hydrologic traces resulted in minimum spring reservoir elevations <3490 feet, so the only bypass releases predicted were those associated with HFEs, flow spikes, cool mix, or cold shock treatments. For days when any amount of bypass spill was used, we assigned a daily average dissolved oxygen concentration of 8 mg/L. We then calculated a weighted average DO concentration (August-October) by assigning modeled penstock DO concentrations for days without bypass and 8 mg/L DO for days with bypass.

Methods Caveats

Future work to constrain the relationship between bypass spill rate and re-aeration would help to more accurately model outflow DO concentrations resulting from bypass spill. This modeling exercise did not attempt to characterize monsoon-driven low DO events. Particularly low oxygen zones have been observed following monsoon storms (e.g., profile data from 2021; Andrews and Deemer, 2023), suggesting that monsoons may be another driver of low DO events.

Results of Analyzing LTEMP SEIS Alternatives

Across all the alternatives examined in this SEIS, 74% of the year by trace combinations are predicted to have mean DO concentrations <5 mg/L in the late summer and early fall (1007 out of 1500).

The likelihood of low DO releases (with summertime mean <5.2 mg/L) did not differ between the No Action, New HFE window only and Non-Bypass (73% of years for both Alternatives; Figure 8-3). The Cold Shock Alternatives (both with and without flow spikes) also led to similar likelihoods of low DO events (71-73% of years; Figure 8-3). Low DO releases were less probable under the Cool Mix Alternative scenarios (57-62% of years; Figure 8-3). For the Cool Mix Alternative, the scenario that targets River Mile (RM) 61 (57% of years) led to fewer years with average DO <5.2 mg/L than the scenario that targets RM 15 (61% of years). This finding was very similar for the Cool Mix with Flow Spikes Alternative scenarios. Differences in the target scenarios are more pronounced during some years than others (Figure 8-4). Model outputs from this exercise are available in Deemer and others (2024).

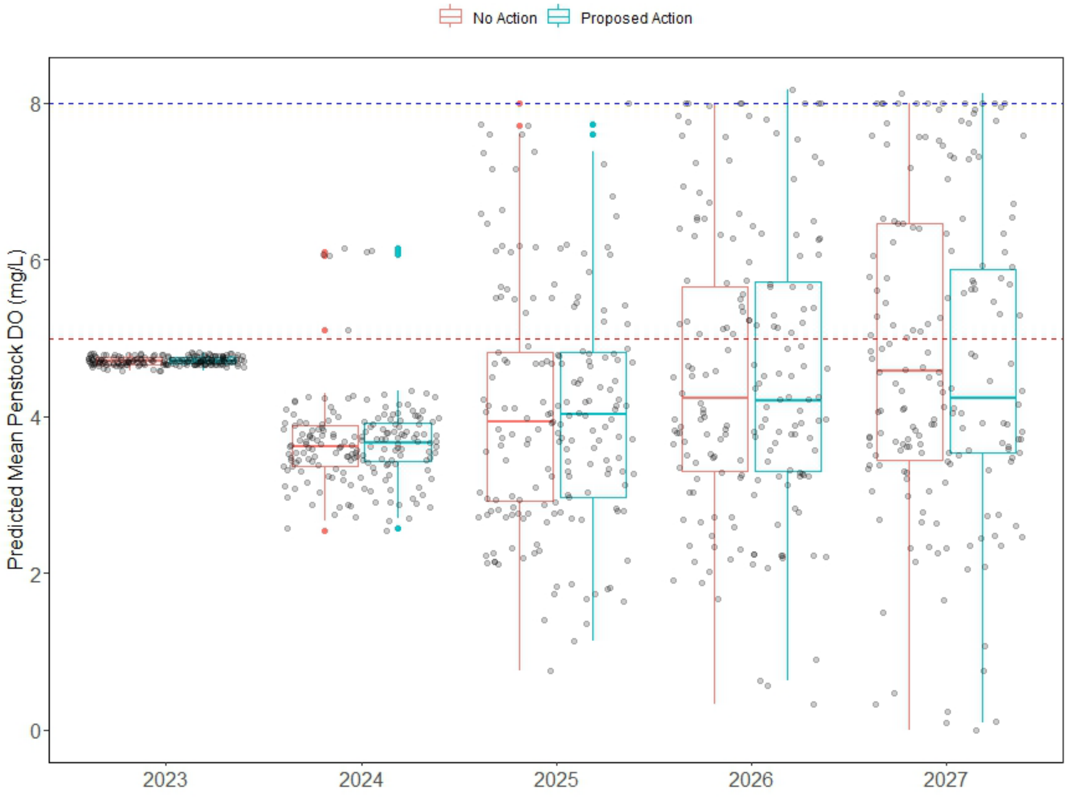

Figure 8-1. Predictions of mean August-October dissolved oxygen (DO) concentrations in GCD outflows for each prediction year under Interim Guidelines SEIS Proposed Action (pink, left-most of pairs) and No Action (blue, right-most of pairs) Alternatives. Each point represents one year for a total of 90 points per box whisker (30 historical reconstructions x 100%, 90%, and 80%). The dashed blue line demarcates 8 mg/L DO which was the modeled concentration for traces that resulted in bypass spill. The dashed red line demarcates 5 mg/L, a threshold below which DO concentrations are stressful to trout.

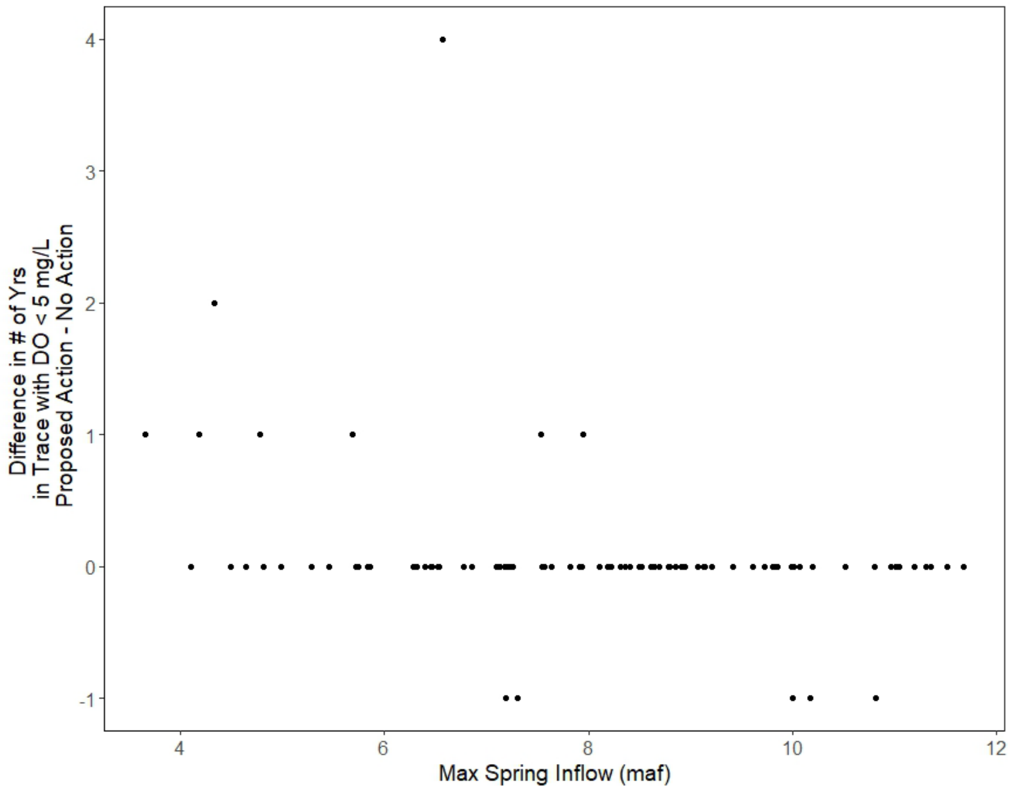

Figure 8-2. Differences in the number of years within each Interim Guidelines SEIS trace that are likely to have a low dissolved oxygen (DO) event as a function of the maximum spring inflow (in millions of acre feet) in the trace. A value of zero indicates no difference between the alternatives, whereas a negative value indicates that the No Action Alternative led to more years with DO dropping below 5mg/L than the Proposed Action (represented as –1 on the y-axis).

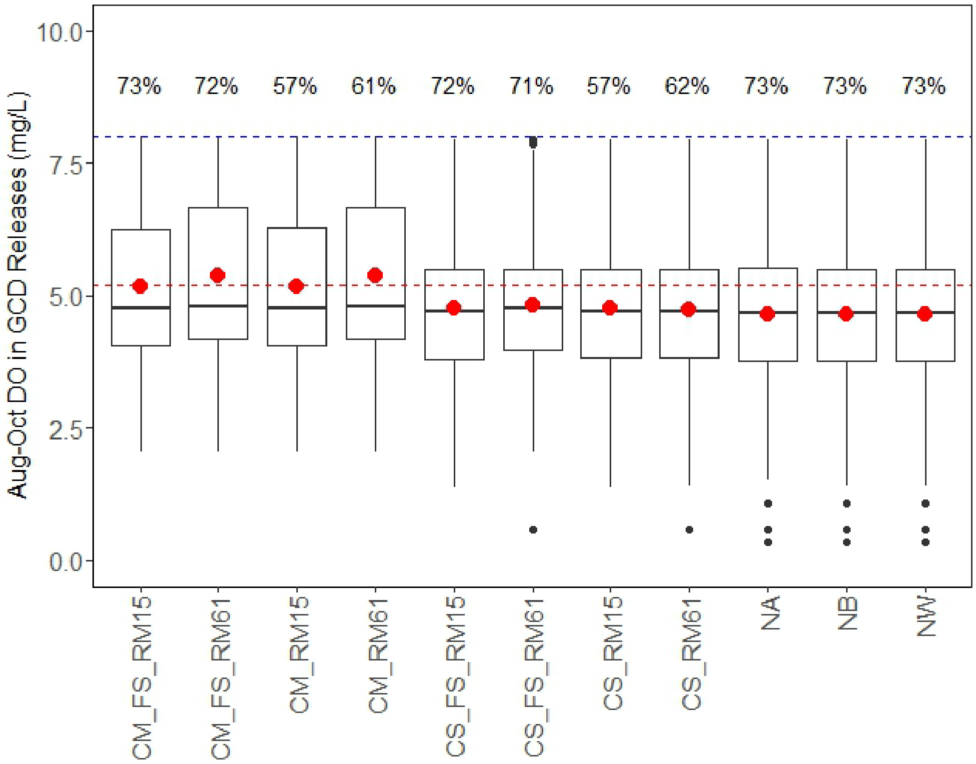

Figure 8-3. Mean August-October dissolved oxygen (DO) concentrations in Glen Canyon Dam outflows across the entire prediction time frame under seven LTEMP SEIS alternatives (and associated river mile target scenarios). Red dots indicate the mean release concentration across years and traces. Box plots were constructed with data points representing one year for a given hydrologic trace for a total of 150 points per box whisker (30 historical reconstructions and five prediction years). The dashed blue line demarcates 8 mg/L DO which was the modeled concentration for days where any amount of bypass spill was implemented. The dashed red line demarcates 5.2 mg/L, a threshold below which DO concentrations are stressful to trout. The percentage of trace/year combinations where average DO is below 5.2 mg/L is annotated above each scenario.

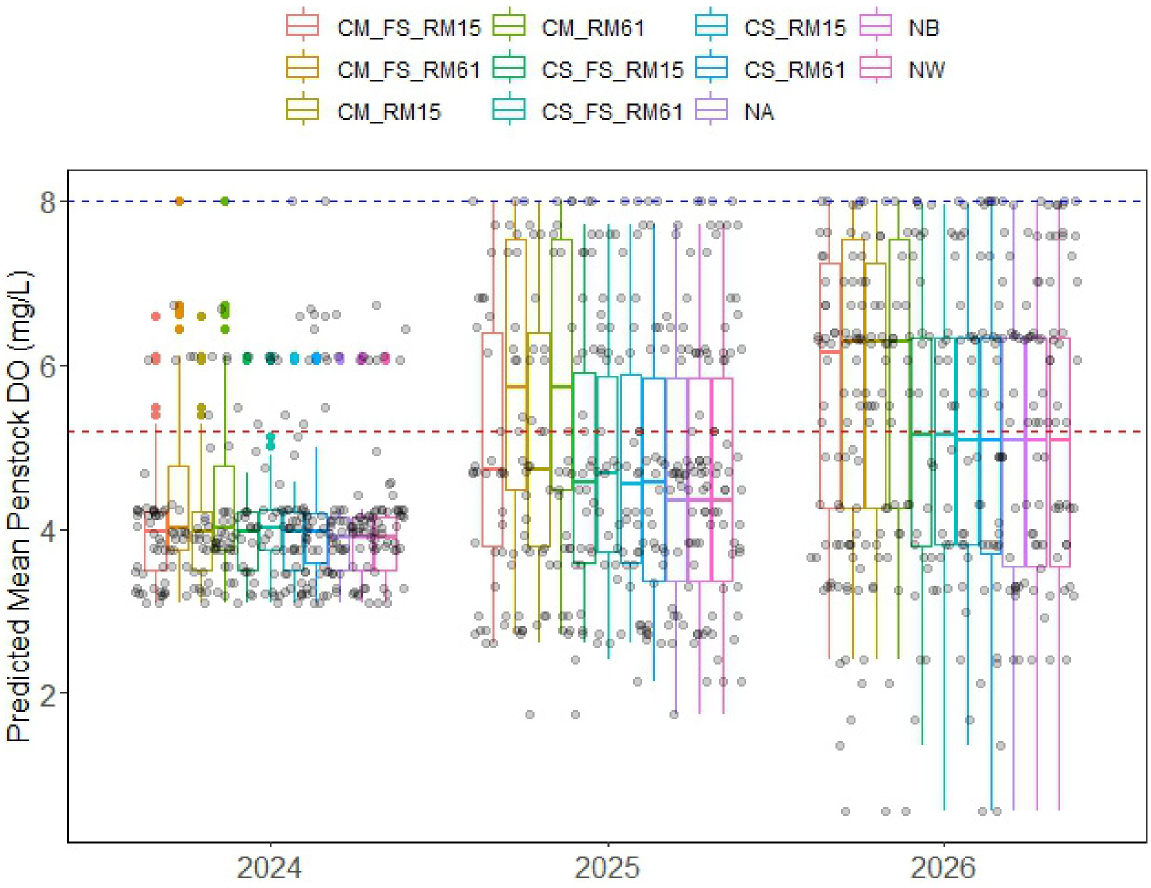

Figure 8-4. Predictions of mean August-October dissolved oxygen (DO) concentrations in Glen Canyon Dam outflows for prediction years 2024-2026 under the LTEMP SEIS alternatives and scenarios (unique colors for each alternative). Each point represents one year for a total of 30 points per box whisker (30 historical reconstructions). The dashed blue line demarcates 8 mg/L DO which was the modeled concentration for days where any amount of bypass spill was implemented. The dashed red line demarcates 5.2 mg/L, a threshold below which DO concentrations are stressful to trout. Note that the range of possible DO conditions is greater each year due to uncertainty in reservoir surface elevation among traces.

Data Availability Statement:

Data generated during this study are published and available (Andrews and Deemer, 2023; Deemer and others, 2024). Specifically, the data that we used in our modeling exercises is available in the “Profiles” .csv file in the Andrews and Deemer data release (2023). The output from the modeling exercises described in this document is available in Deemer and others (2024).

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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