Technical Appendix 5

Geomorphology and Sediment

This page intentionally left blank.

Contents

Tables

Figures

Acronyms and Abbreviations

Acronym or Abbreviation	Full Phrase
CCS	Continued Current Strategies
cfs	cubic feet per second
HFE	High Flow Experiment
LB Priority	Lower Basin Priority
LB Pro Rata	Lower Basin Pro Rata
LTEMP	Long-Term Experimental Management Plan
maf	Million acre-feet
RM	River Mile

This page intentionally left blank.

TA 5. Geomorphology and Sediment

TA 5.1 Affected Environment

This section presents an overview of sediment and geomorphic features in the Colorado River study area. The influx and efflux of sediment result in spatial and temporal variations in sandbars and channel-margin deposits throughout the Colorado River (Grams et al. 2013). Sandbar formation is a complex process that depends on:

- Flow Conditions
- Sediment Supply
- Sediment Transport
- Geomorphic Features

TA 5.1.1 Flow Conditions

Prior to the construction of the dams, the Colorado River conveyed high suspended sediment concentrations throughout most seasons during base flows and with larger flood flows (USGS 2011). The construction of Glen Canyon Dam effectively cut off approximately 95 percent of the historical sediment supply from the upper watershed (Topping et al. 2000). As a result, the Colorado River now typically transports sand downstream faster than tributaries can resupply sand on a seasonal to annual basis. This sediment deficit has resulted in progressive erosion of channel and sandbar deposits from Marble and Grand Canyons since 1963. From 1964 to 2017, net erosion occurred for approximately 69 percent of all years in Marble Canyon and for approximately 52 percent of all years in Grand Canyon (Topping et al. 2021).

Maximum releases from the dam are substantially less than historical annual peak flows, and the high-water zone has been lowered compared with the historical level. Under pre-dam conditions, sand would accumulate in Marble Canyon and upper Grand Canyon from July through March when flows were largely below 7,000 to 11,000 cubic feet per second (cfs), then erode from April to June when flows were typically higher (Topping et al. 2000). Current dam operations, under which most flows are greater than 7,000 to 11,000 cfs, do not allow for substantial sand accumulation. In conjunction with reduced sand supply, post-dam discharges have reduced the zone of annual deposition, increased the rate of sediment erosion, and contributed to the loss of beaches and sandbars (USGS 2011).

Since 1996, the Bureau of Reclamation (Reclamation) has conducted high flow experiment (HFE) releases, managing limited sediment resources to maintain or increase sandbar size. HFE releases, which are designed to improve sediment deposition, provide the only mechanism available for sandbar building and are the most important tool for sediment resources. These water releases from Glen Canyon Dam are much larger than the base flow that is typically released. HFE releases may be as low as 31,500 cfs, though releases of 37,000 cfs or greater are necessary for sandbar deposition (increased sandbar size) (Hazel et al. 2022; Salter et al. 2025). Sandbars erode between HFE releases (Hazel et al. 2022), with the highest rates immediately after a flood (when bars have the most sediment available for erosion) and decreasing with time (Grams et al. 2010). Steadier flows erode bars at a lower rate than fluctuating flows (Wright et al. 2008).

Long-term rehabilitation of eddy sandbars can occur only if the increases in sandbar volume caused by high flows exceed the erosion that occurs during the intervening periods, and HFE releases are the only existing mechanism for producing river stages high enough to contribute to significant sandbar building. Alternatively, if there are only small amounts of deposition during high flows and large volumes of erosion during intervening periods, a long-term decrease in sandbar size will result. More frequent HFE releases result in net increases of sandbar size given sufficiently great sand enrichment (Grams et al. 2025).

TA 5.1.2 Sediment Supply

The Paria and Little Colorado Rivers, tributaries to the Colorado River, are the major sources of sediment replenishment downstream of the dam. These tributaries affect the mechanisms that control sandbars in Marble and Grand Canyons. No major sediment source exists upstream of the Paria River, effectively making sediment a nonrenewable resource in modern-day Glen Canyon (Grams et al. 2007). Sand supplied by tributaries remains in storage for typically a few months to a year in Marble Canyon before much of it is transported downstream unless flows are below approximately 9,000 cfs (Topping et al. 2000, 2021; Rubin et al. 2002; USGS 2011).

TA 5.1.3 Sediment Transport

The Colorado River in the Grand Canyon is a sediment-supply-limited bedrock river. Releases from Glen Canyon Dam are clear, sediment-free water (Salter 2025). Sediment supplied to the Colorado River comes from tributaries. Sediments are typically classified by particle size and include the following classes:

- Silt and clay (less than 0.0625 millimeters)
- Sand (0.0625 to 2.0 millimeters)
- Gravel and cobbles (2.0 to 256 millimeters)
- Boulders (greater than 256 millimeters)

In general, the term “fine sediment” refers to sediments that are sand-sized or smaller. This group makes up most of the transported sediment in the river and is carried in suspension by most dam releases. Therefore, in this analysis, unless otherwise noted as “coarse sediment,” sediment and fine sediment are used interchangeably. Sand contributes the most to sediment storage, deposition rates, and downstream sand export (Topping et al. 2021). The quantity of silt and clay transported depends mainly on the tributary supply. Sandbars contain some silt and clay, but their existence primarily depends on the transport of sand. Sand sediments in the Colorado River are delivered by tributary streams, arroyos, and ephemeral[1] washes. As described above, the Paria and Little Colorado Rivers are the dominant sources. The smaller tributaries in Marble Canyon upstream from River Mile 30

[1] A wash that flows part of the time, usually after a rainstorm, during wet weather, or for only part of the year.

together contribute roughly 10 percent of the sand annually supplied by the Paria River (Griffiths and Topping 2017). Downstream from River Mile 30, the Marble Canyon lesser tributaries supply negligible amounts of sand (Griffiths and Topping 2017; Topping et al. 2021).

The amount of sand stored within the riverbed each year depends on the highly variable tributary supply, the frequency and duration of water released from the dam, and the amount of sand already deposited on the riverbed at the beginning of the year. Sand stored on the riverbed is the principal source for building sandbars during periods of high flow releases. Sediment transport is a function of, and increases with, the volume of water flowing in the river. It also depends on changes in the sediment size and supply associated with tributary floods and dam operations, as well as the distribution of shear stress[2] across the wetted channel.

The shear stress caused by flowing water can increase the amount of sediment in suspension and the amount that is available for transport. Sediment deposition occurs wherever there is more sediment influx than efflux, but is dependent on local hydraulics, such as eddies (discussed in the next section) and the topography of the riverbed (Grams et al. 2013). The greater the river's flow, the greater its velocity, shear stress, and sediment load.

Sediment storage on the riverbed depends on the spatial variability of the riverbed (such as variations of boulders, cobbles, bedrock, and vegetation), the depth to the riverbed, and the tributary sediment supply (Rubin et al. 2020). This sediment storage, in addition to storage within sandbars and along channel margins on the Colorado River, results from coupled flow, sediment transport, and storage within fan-eddy complexes (**Figure TA 5-1**) [3] that lead to deposition of sediments.

TA 5.1.4 Geomorphic Features

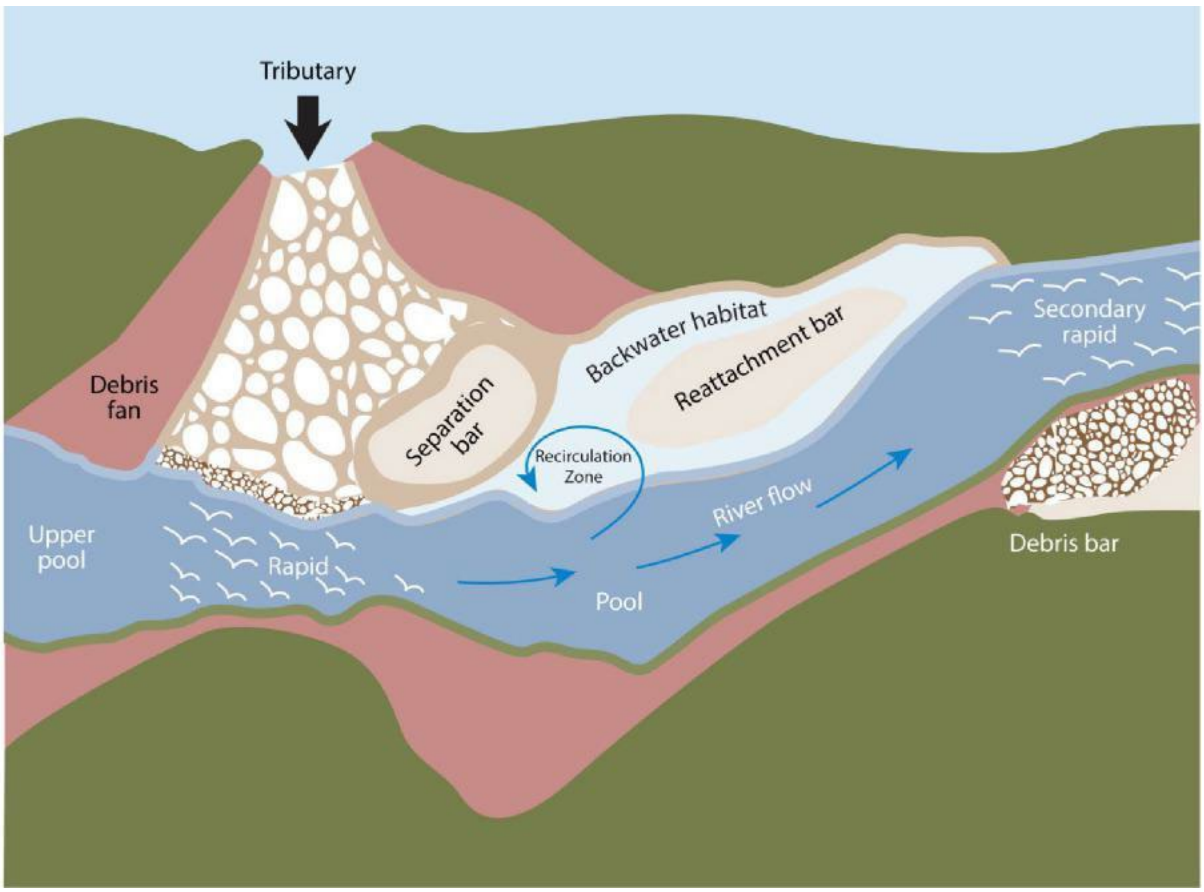
The longitudinal profile of the Colorado River consists of long, flat pool reaches with intermixed short, steep rapids. The rapids in fan-eddy complexes are typically associated with boulder rich deposits formed by tributary debris flows,[4] and flash floods. Debris fans continue to be replenished and enlarged by debris flows triggered by slope failures into tributaries. The geologic conditions favorable for debris flows from side canyons vary greatly. Debris flows tend to be high-magnitude, short-duration events. Debris flows create and maintain the rapids, control the size and location of eddies, and serve as potential sources of sand to replenish Colorado River sandbars in Marble and Grand Canyons (Schmidt and Rubin 1995; Webb and Griffiths 2001).

The coarse sediments associated with debris-fan deposits can only be mobilized during elevated flows and do not constitute a significant contribution to sediment loads transported by the river. However, their dynamics are important with respect to their retention of fine sediments and the development of fan-eddy complexes (Reclamation 2016). Debris fans extending into the Colorado River obstruct the channel, making it narrower and raising the bed elevation, which forms rapids through the point of constriction and causes the downstream-directed current to become separated

[2] The force per unit area acting parallel to a surface that causes slippage.
[3] Areas along the river where a tributary's debris fan—a sloping deposit of poorly sorted sediment ranging in size from clays and silts to larger boulders—partially blocks the river flow, causing the formation of rapids and eddies (Schmidt and Rubin 1995). Fan-eddy complexes are the controlling geomorphic feature in the Colorado River for sediment deposition.
[4] A large mass flow of sediment caused by slope failures on tributary canyons.

from the riverbank (Webb and Griffiths 2001). Downstream of the constriction, the channel is typically wider, the main current reattaches to the riverbank, and some of the water is redirected upstream. This change in flow direction forms a zone of low-velocity recirculating water (an eddy) between the points of separation and reattachment and between the main channel and riverbank (Rubin et al. 1998). These conditions allow for sediment to become entrained within the recirculation zone, where lower-velocity flows enhance the potential for sediment deposition (Schmidt and Rubin 1995).

Figure TA 5-1
Diagram of the Fan-Eddy Complex on the Colorado River



Source: Web and Griffiths 2001

Sand is deposited throughout Glen, Marble, and Grand Canyons in bars (or patches) on the riverbed, in eddies, and on terrace sandbars. Nearly all sandbars in the Grand Canyon are associated with fan-eddy complexes. In general, these complexes generate consistent sandbar features, which include separation bars and reattachment bars, based on their specific locations within the recirculation zone (USGS 2011). They continuously exchange sand with the river. Thus, the sandbars commonly found along the banks of the Colorado River are generally dynamic and unstable.

The magnitude of deposition varies by site, depending on geomorphic conditions and vegetative cover; some sandbars are stabilized by vegetation (Mueller et al. 2018; Hazel et al. 2022). Sandbars form a fundamental element of the river landscape and are important for vegetation, riparian habitat for fish and wildlife, cultural resources, and recreation (Reclamation 1995, 2024). They form the substrate for limited riparian vegetation in this arid environment. Low-elevation sandbars create zones of low-velocity aquatic habitat (i.e., backwaters) that may be utilized by juvenile native fishes for spawning and refuge (Van Steeter and Pitlick 1998; Rubin et al. 2002). These low-elevation sandbars have been documented to be the source of sand for wind transport that helps protect archaeological resources in certain areas (East et al. 2016; Collins et al. 2016; Sankey and Draut 2014; Sankey et al. 2023a; Sankey et al. 2023b). In addition, beaches provide camping areas for river and backcountry users.

TA 5.1.5 Turbidity

Turbidity is known to increase in the study area during high flows when suspended sediment concentration increases. Clear water conditions exist most of the time in the study area, interrupted by temporary periods of low visual clarity after tributary flooding (Voichick and Topping 2014). During runoff events, turbidity often exceeds the maximum recording levels of optical turbidity probes of 1,000 to 2,000 formazin nephelometric units[5]. Optical measurements of turbidity can be correlated with streamflow or with suspended sediment concentration; however, these relationships should be used with caution because, in the Colorado River, a) physical sediment characteristics are highly variable over time and b) the upper limit of measurable turbidity on optical turbidity probes is reached (Voichick and Topping 2014).

High concentrations of fine suspended sediment can increase turbidity, an optical measurement of dissolved or suspended particles in water. The relationship between turbidity and suspended sediment concentration depends on the physical properties of sediment and changes under differing conditions and sediment sources. Although higher turbidity is generally viewed as undesirable for recreational activities such as fishing, it more closely reflects the pre-dam conditions of the river.

Turbidity in the Colorado River is a natural condition and not further considered in this section.

TA 5.1.6 Study Area

The geographic scope that would be affected by the proposed alternatives extends from Lake Powell to the Southerly International Boundary with the United Mexican States (Mexico). Upstream of Hoover Dam, HFEs would have significant impacts on geomorphology and sedimentation in Marble Canyon and Grand Canyon. Since most fine sediment is transported downstream, this material will ultimately be trapped behind Hoover Dam in Lake Mead.

Downstream of Hoover Dam, the Colorado River functions as a sediment-starved, clearwater system. The magnitude of releases from Hoover Dam influences sediment transport capacity but does not meaningfully alter sediment supply. Consequently, this reach is defined by stable, armored bed surfaces, simplified channel morphology, and limited sandbar formation. Sediment originates primarily from reworking of fine-grained material along channel margins and bank erosion associated with sparse depositional pockets. Vegetation encroachment along banks has increased in

[5] A measure of turbidity. These formazin nephelometric unit values indicate the water has more suspended sediment and light cannot penetrate easily.

recent decades under stabilized baseflows, further constraining areas where sediment can accumulate or be remobilized.

The only significant sediment inputs downstream of Hoover Dam are large, infrequent events on the Bill Williams River and the Gila River, affecting the reaches from Parker Dam to Imperial Dam and from Imperial Dam to the Northerly International Boundary. Ongoing Reclamation dredging operations remove this sediment at and upstream of Imperial Dam as well as upstream of Morelos Diversion Dam to improve diversion capability and to efficiently convey water to downstream users, operations which will continue under the proposed alternatives.

TA 5.2 Environmental Consequences

TA 5.2.1 Methodology

All modeling used for this resource section was based on modeling performed by the USGS Grand Canyon Monitoring and Research Center (Grams et al. 2025; and Salter et al. 2025), using a sand routing model (Wright et al., 2010) and sandbar response model (Mueller and Grams 2021). Input hydrologies were developed using modeling results from the Colorado River Simulation System, a long-term planning tool operated by the Bureau of Reclamation to support decision making in the Colorado River Basin and implemented in RiverWare (Zagona et al. 2001). For additional information on Colorado River Simulation System results and assumptions, please reference Appendix D of Reclamation (2016).

The initial conditions (bed thicknesses and bed grain-size distribution) for the sand routing model were based on Wright et al. (2010), using a spin-up period from September 1, 2002, to October 1, 2024, and sediment inputs and gage discharges downloaded from the Grand Canyon Monitoring and Research Center website (USGS 2024). Because the initial conditions for future simulations are unknown, the following idealized initial conditions were selected based on a simulation of the sand routing model and the spin-up period: a bed thickness of 0.5 meter, a lognormal bed grain size distribution with a median bed grain size of 0.3 millimeter, and a geometric standard deviation of 1. Sediment inflow projections from the Paria and Little Colorado Rivers were also generated using the Wright et al. (2010) sand routing model. This sand routing model provides sediment budget by grain size, suspended sediment concentrations, and changes in bed texture over time. Each of the 400 hydrology traces were randomly assigned a trace of Paria River sediment year inputs for sediment years 1998 to 2024. A sediment year aligns with the seasonal cycle of sediment supply and river flow, rather than the calendar year. It runs from July 1 to June 30 the following year (Topping et al. 2000).

To generate final sand routing and sandbar volume simulations, the sand routing model was rerun for each trace, with new hourly hydrographs generated by a hydropower optimization model and the same Paria River traces as in the previous round of modeling. Changes to the sediment mass balance were minimal, and HFE release durations were not modified.

HFE release magnitude and duration were selected via iteration according to the sand mass balance. Grand Canyon Monitoring and Research Center modelers redistributed monthly volumes if necessary and interfaced the monthly volumes with the sand routing model by generating synthetic 15-minute hydrographs.

The output of the sand routing model provided suspended sand concentration and median grain-size inputs for the Mueller and Grams (2021) sandbar model. This model predicts long-term changes in sandbar volume in the Colorado River through the Grand Canyon based on controlled releases from Glen Canyon Dam. The sandbar model was recalibrated to the 2002–2024 period based on the long-term monitoring program. The model was initialized using the January 1, 2025, volume (1169.5 cubic meters), and each alternative was run for all 400 traces and 3 initial conditions (see **Appendix F**, Approach to Hydrologic Uncertainty, for more information on the initial conditions).

Some modifications were made to the Mueller and Grams (2021) sandbar model for this draft environmental impact statement to use additional sandbars in the calibration dataset (a total of 25 sandbars that were separated into 12 within Marble Canyon and 13 within Grand Canyon); incorporate discharge-dependence into the erosion model, rather than assuming exponential erosion with an unchanging rate constant; and assume a constant sandbar area rather than a linear relationship between sandbar area and sandbar volume (Salter et al. 2025).

Two versions of the sandbar model were used to predict sandbar deposition: one for flow rates exceeding 8,000 cfs, the average daily discharge flow; and one for flow rates exceeding 25,000 cfs, the discharge at which sandbars will not be inundated during normal dam operations and will result in usable sandbars for recreational purposes (Salter et al. 2025). Except for modeled HFEs, the sandbar model did not include any sustained releases above 25,000 cfs over the calibration period.

Impact Analysis Area

The impact analysis area used for Grand Canyon Monitoring and Research Center sediment modeling data is the Colorado River from Glen Canyon Dam to Lake Mead, including sediment inputs from the Paria River and Little Colorado River tributaries. The analysis area for the sandbar model (quantitative model) is from Lees Ferry (River Mile [RM] 0) through Diamond Creek (RM 225). The extent of this model is limited by the availability of study sites in the calibration dataset. However, it is expected that the finding for the reach between Lees Ferry and Diamond Creek is also representative of similar sandbars downstream to Separation Canyon (RM 240), the full-pool extent of Lake Mead. With low Lake Mead elevations, the Colorado River will cut new paths through the deltas at its mouth in the reservoir. This will result in sediment redistribution in the reservoir for which no model is currently available, forming new bars and altering the delta. Finer particles may remain in suspension and travel further downstream in the reservoir before settling, increasing sediment concentration in the upper reaches of Lake Mead.

The proposed alternatives may modify the magnitude, timing, or variability of releases from Hoover Dam relative to existing operations. Any such changes would affect sediment resources downstream by altering sediment transport capacity and the degree to which available fine sediment is mobilized or retained. However, because the downstream reach is sediment-starved and the alternatives would not change Hoover Dam operations, introduce new sources of sediment or significantly modify sediment supply, or change channel morphology, any effects on geomorphology and sedimentation downstream of Hoover Dam are expected to be negligible. In all cases, sediment-related effects are expected to remain localized, reflecting the reach's supply-limited sediment regime.

Modeling Criteria and Assumptions

- For an HFE to be triggered, enough sand needs to be available in Marble Canyon (there must be a positive sand mass balance over the sediment accounting period), and enough water needs to be available in Lake Powell (as measured by the water level). Both the required amounts of sand and water depend on the selected HFE duration.
- Consistent with the 2024 Glen Canyon Dam Long-Term Experimental Management Plan (LTEMP) Supplemental Environmental Impact Statement (2024 LTEMP SEIS) and Salter et al. (2025), HFE releases can only be implemented above a Lake Powell elevation of 3,500 feet, the elevation required for a release magnitude of 37,000 cfs.
- Annual and monthly release volumes can limit the ability for an HFE release. HFE releases are offset by reducing releases from the rest of the water year, while ensuring no months go below LTEMP minimum releases in the process.
- Only sand deposited above flow rates of 25,000 cfs, which corresponds to the minimum water level that provides safety from flooding, is considered "usable" for recreational purposes.
- Sandbar deposition occurs most rapidly during the first 4 days of an HFE event, when the suspended sand concentration is largest, and the suspended sand is finest.
- Based on historical data, 60 hours is the minimum duration for an HFE to result in significant sandbar deposition.
- The transport capacity for sand during a 60-hour HFE event depends on the grain size of the accumulated sand. The average transport capacity for the 60-hour event is 294,000 metric tons, based on the analysis using the Wright et al. (2010) sand routing model.
- Sandbar erosion rates tend to be highest immediately after a flood (when bars have the most sediment available for erosion), then decrease with time (Grams et al. 2010). Steadier flows erode sandbars at a lower rate than fluctuating flows (Schmidt et al. 1995).
- Total discharge maximum ramp rates of 4,000 cfs per hour up and 2,500 cfs per hour down are consistent with the 2016 Glen Canyon Dam LTEMP Environmental Impact Statement and 2024 LTEMP SEIS.
- Most of the sand input from the Paria and Little Colorado Rivers occurs during the summer-fall thunderstorm season between July 1st and November 1st. A fall HFE would take full advantage of this by initiating an HFE prior to winter releases that could transport the sand downstream without the ability to aid in sandbar formation.
- During low water levels in Lake Powell, large winter releases are not a major concern. Snowpack accumulation is known prior to a possible spring HFE. This creates the option to prefer a spring HFE over a fall HFE during prolonged dry conditions, although fall HFE implementation is considered independent of a spring implementation. "Deferring," or choosing not to conduct an HFE, does not prioritize conducting an HFE during the next implementation window.
- If no HFE releases were implemented during the 1-year sediment accounting period, any positive sediment mass balance would be carried over into the next accounting period.

Impact Indicators

Issues related to geomorphology and sedimentation that are evaluated in this section are listed below.

1. Water Availability in Lake Powell
2. Sand Mass
3. HFE Frequency and Duration
4. Sandbar Volume
5. Sand Transport

TA 5.2.2 Issue 1: Water Availability

An HFE likely to enlarge sandbars requires enough water for a release magnitude of 37,000 cfs, generally considered the flow rate needed for significant deposition on certain sandbar types (Hazel et al. 2022). A release rate of 37,000 cfs, in turn, requires a minimum Lake Powell water level of 3,500 feet in April or November, the months in which HFEs typically occur. Alternatives that more frequently result in water levels greater than this threshold are therefore preferable.

It should be noted that there are challenges to conducting HFEs at the minimum Lake Powell elevation of 3,500 feet. Historically, the lowest elevation at which an HFE has been implemented was approximately 3,523 feet in April 2023. Since the models used elevations of 3,523 feet and lower as the lowest possible elevation at which HFEs could occur, it is likely that the modeling overestimates the number or frequency of HFEs and underestimates the impacts on sediment related resources in the Grand Canyon for some alternatives. **Table TA 5-1** below shows the percentage of modeled HFEs by alternative that were above (or below) this lowest historical elevation.

The modeling was based on HFEs being implemented at any Lake Powell elevation greater than 3500 feet. However, in practice, fall HFEs have not been implemented when Lake Powell water levels were below 3590 feet. In April 2023, an HFE was implemented when Lake Powell was at 3525 feet, but that HFE was scheduled based on the large snowpack and predicted spring/summer runoff. **Table TA 5-1 s**hows that in the No Action, Basic Coordination, and Supply Driven Alternatives almost 10 percent or more of the HFEs occur at Lake Powell elevations between 3,500 and 3,523 feet. In the Maximum Operational Flexibility Alternative, 7 percent of the HFEs are at lower Lake Powell elevations, and in the Enhanced Coordination Alternative, less than 1 percent of the HFEs are in that category. The table also shows that across all alternatives, an HFE is modeled to occur on average once every two years or once every four timesteps.

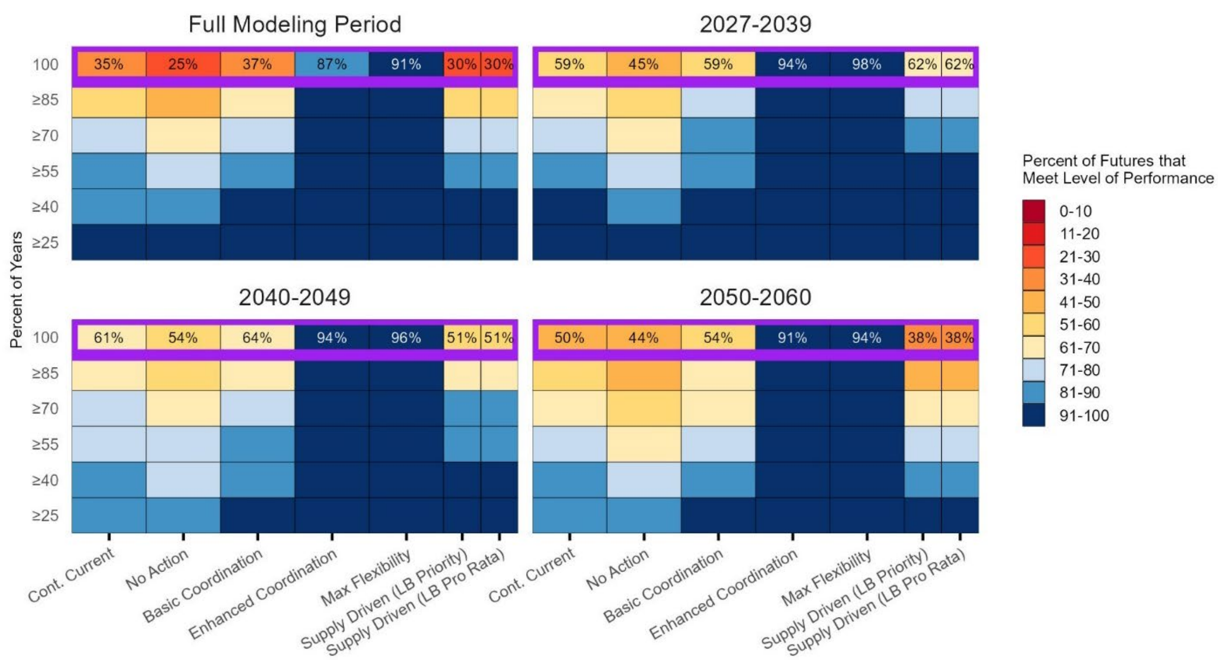
Figure TA 5-2 shows the percentage of futures in which Lake Powell elevation is greater than 3,500 feet in November or April in the percent of years specified by each row. The highlighted row indicates the percentage of futures that meet this criterion for all years in the simulation period (i.e., 100 percent of years in the simulation period). The highlighted row demarks the preferred minimum performance utilized in **Figure TA 5-4**.

Table TA 5-1
Percentage of Modeled HFEs Above or Below the Historic Low Lake Powell Elevation (3,523 feet)

Alternative	Total number of HFEs (all years, all futures)[1]	Percent of all eligible timesteps with an HFE	Percentage of Modeled HFEs Above	Percentage of Modeled HFEs Below	Average number of HFEs/year Only Above	Average number of HFEs/year Above + Below
Continued Current Strategies (CCS) Comparative Baseline	20,655	25.3%	88.6%	11.4%	0.45	0.51
No Action Alternative	20,610	25.3%	90.1%	9.9%	0.46	0.51
Basic Coordination Alternative	23,315	28.6%	88.5%	11.5%	0.51	0.57
Enhanced Coordination Alternative	24,260	29.7%	99.7%	0.3%	0.59	0.59
Maximum Operational Flexibility Alternative	26,618	32.6%	93.3%	6.7%	0.61	0.65
Supply Driven Alternative	22,970	28.1%	83.8%	16.2%	0.47	0.56

Source: Bureau of Reclamation.
[1] The total number of HFE eligible timesteps is 81,600 (April and November, all futures, all years)

Figure TA 5-2
Lake Powell Elevation Meeting Requirement for HFE: Robustness.
Percent of futures in which the November or April elevation exceeds 3,500 feet in the percent of years specified in each row



Performance under each Alternative

- For the full modeling period, the Enhanced Coordination and Maximum Operational Flexibility Alternatives are the most robust, meeting the preferred minimum performance level in 87 percent and 91 percent of futures, respectively. This indicates that these two alternatives would likely result in the most water availability to conduct a fall or spring HFE. These alternatives are substantially more robust compared to all other alternatives.
- For the full modeling period, the No Action Alternative is the least robust, with only 25 percent of futures meeting the preferred minimum performance level. The futures for the Supply Driven Alternative (both Lower Basin [LB] Priority and LB Pro Rata approaches; 30 percent), CCS Comparative Baseline (35 percent), and Basic Coordination Alternative (37 percent) are similarly less robust.
- In the 2027–2039 and 2040–2049 subperiods, all alternatives have greater percentages of futures that meet the preferred minimum performance level than the 2050–2060 subperiod. The lower water levels are likely a result of drier conditions, pointing to the importance of interdecadal hydrologic variability on performance. This lack of performance is more pronounced for the CCS Comparative Baseline and the No Action, Supply Driven, and Basic Coordination Alternatives.
- The Enhanced Coordination and Maximum Operational Flexibility Alternatives have consistently high performance in all periods, when compared to the No Action Alternative and CCS Comparative Baseline, which further demonstrates their robustness.

- For all alternatives, greater than 50 percent of futures meet the desired level of performance when the threshold is greater than or equal to 70 percent of years. Since HFEs aren't expected to be performed on a yearly basis, this indicator demonstrates a higher degree of robustness compared to other indicators.

Figure TA 5-3 shows the same information as **Figure TA 5-2** but for an elevation threshold of 3,523 feet, the lowest Lake Powell elevation in the historic record. Once again, the Enhanced Coordination and Maximum Operational Flexibility Alternatives clearly outperform the other alternatives and the CCS Comparative Baseline, but the percentage of futures that meet the preferred minimum performance level (63 percent and 51 percent, respectively) is substantially lower than in **Figure TA 5-2**. In addition, whereas the Maximum Operational Flexibility Alternative is most robust for an elevation threshold of 3,500 feet (**Figure TA 5-2**), the Enhanced Coordination Alternative is most robust for an elevation threshold of 3,523 feet (**Figure TA 5-3**).

Figure TA 5-3
Lake Powell Elevation Above Lowest Observed in HFE Implementation: Robustness. Percent of futures in which the November or April elevation exceeds 3,523 feet in the percent of years specified in each row

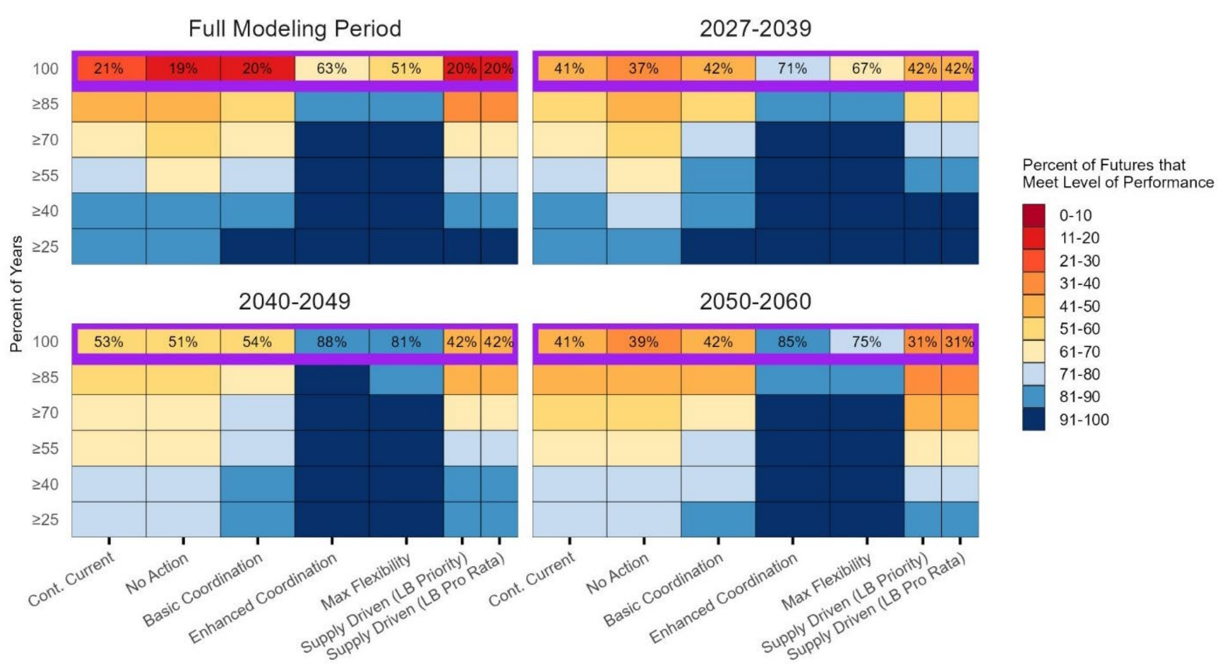
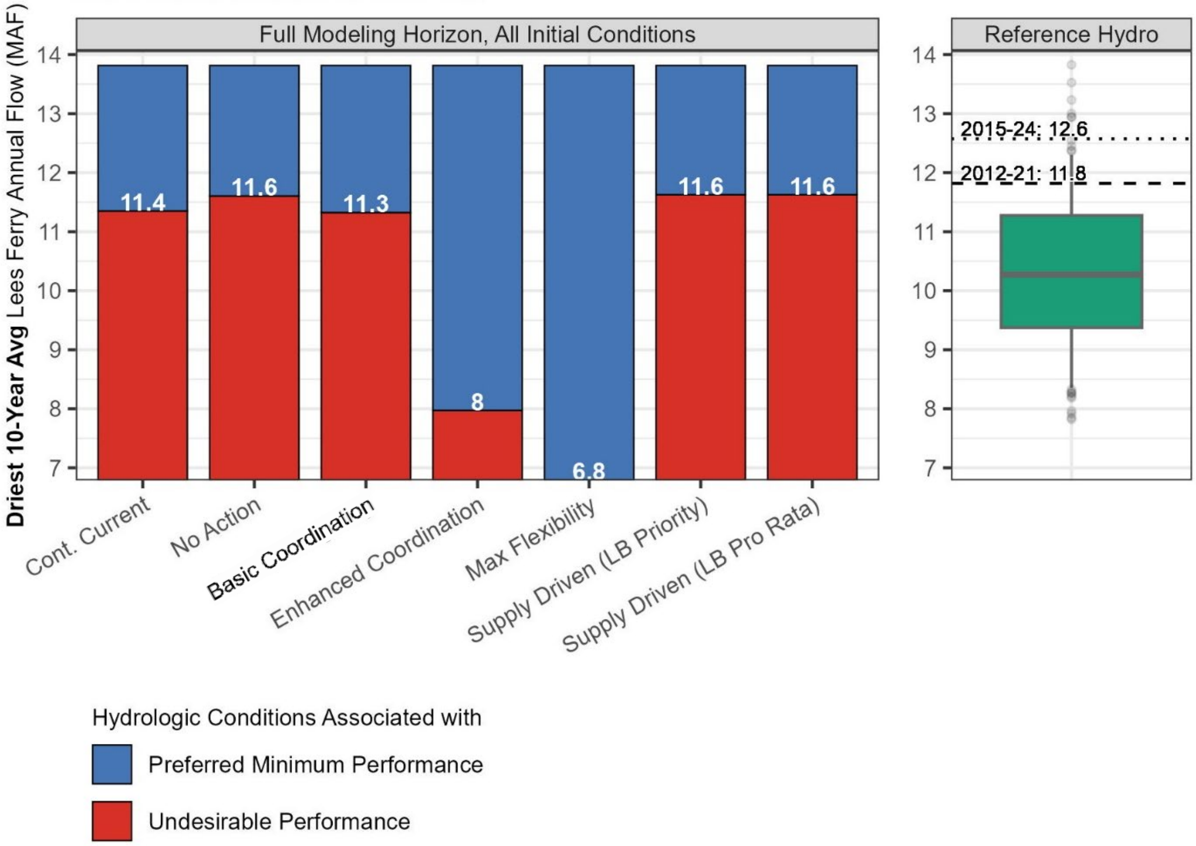


Figure TA 5-2 highlighted the preferred minimum performance level of Lake Powell being above elevation 3,500 feet in either April or November in 100% of years. To identify hydrologic conditions that could cause undesirable performance where Lake Powell elevation limits HFE opportunities, the incidence of Lake Powell falling below 3,500 feet in both November and April in at least 1 year out of the 34-year modeling horizon was analyzed, and the results are shown in **Figure TA 5-4**. The driest 10-year average Lees Ferry Natural Flow in each modeled future (shown on the y-axis) was identified as a good predictor of undesirable performance.

Figure TA 5-4
Lake Powell Elevation Meeting Requirement for HFE: Vulnerability.
Conditions that could cause Lake Powell elevation below 3,500 feet in November and April in One or More Sediment Years



The reference hydrology shows the distribution of the driest 10-year average natural flows for an ensemble of projected conditions (see **Chapter 3, Figure 3-4**, for more information on the selected reference hydrology). For reference, the 10-year average flows for the period ending in 2021 (11.8 million acre-feet [maf]) and 2024 (12.6 maf) are also included in the plot.

Performance under each Alternative

- The Enhanced Coordination and Maximum Operation Flexibility alternatives are the least vulnerable, and they are expected to satisfy the preferred minimum performance level except for futures that experience a 10-year drought drier than 8.0 maf per year or 6.8 maf per year, respectively. Comparing these streamflow values to the reference hydrology, Enhanced Coordination is vulnerable in less than 10% of futures and Maximum Operational Flexibility is vulnerable in zero futures.
- The other alternatives and the CCS Comparative Baseline are highly vulnerable to the reference hydrology, with over 75% of the futures in the reference hydrology expected to result in undesirable performance.

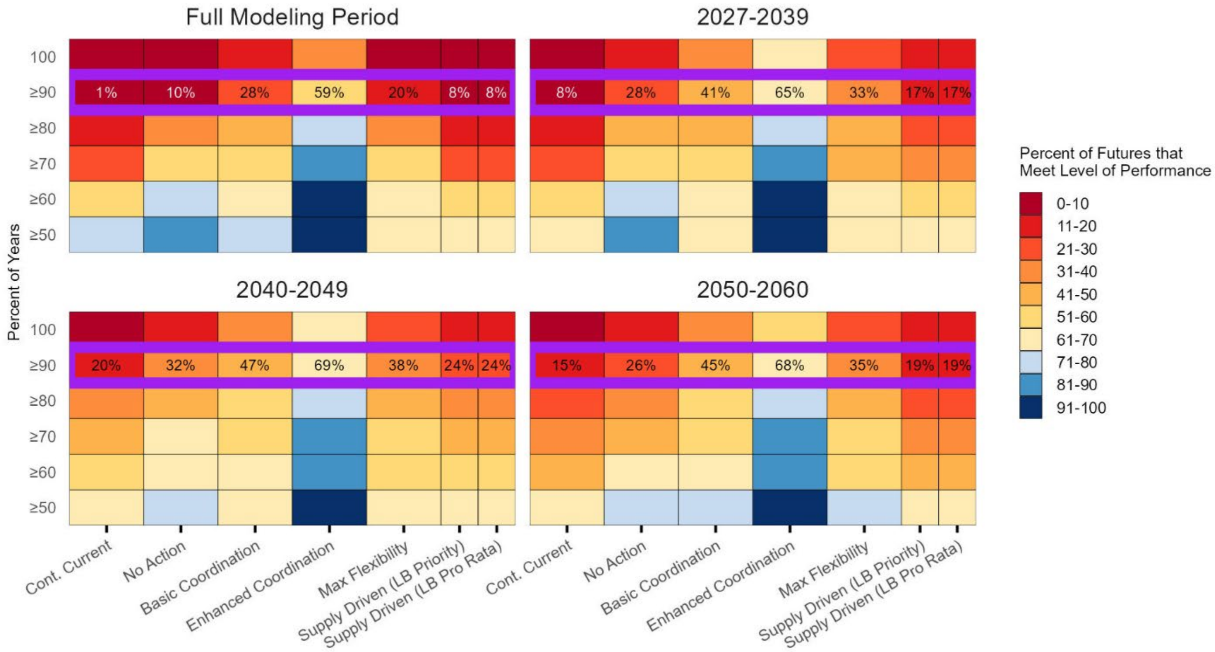
- All the alternatives and the CCS Comparative Baseline would be expected to meet the preferred minimum performance level in a future where the worst 10-year drought is no drier than the historical minimum (11.8 maf per year, which occurred from 2012 to 2021).

TA 5.2.3 Issue 2: Sand Mass

Sand in the Colorado River must be available to be carried downstream and deposited to form sandbars during an HFE release. Sand that accumulates in Marble Canyon but is transported downstream outside HFE events does not result in sandbar formation. The sand available for the sandbar building is supplied to the Colorado River by thunderstorm-induced flood season in the Paria and Little Colorado watersheds in the late summer and early fall. The proposed alternatives would not impact the sand and sediment inflow from these tributaries. However, the proposed alternatives affect the timing and magnitude of releases outside of HFE events and, therefore, impact sand transport that occurs outside of these events.

Figure TA 5-5 shows the percentage of futures in which the maximum monthly release from Glen Canyon Dam is less than 900,000 acre-feet per month (approximately 15,000 cfs) in the percent of sediment years specified by each row. In other words, it shows the percentage of futures in which Glen Canyon Dam release rates are generally non-erosive. While average monthly flows must be lower than about 11,000 cfs to allow sediment accumulation under most initial conditions, monthly flows averaging greater than 15,000 cfs are likely to be erosive regardless of those initial conditions (Salter et al. 2025). Therefore, 900,000 acre-feet per month is used as the threshold above which flows are erosive for accumulated sand. A future is considered to satisfy the preferred minimum performance level if the monthly maximum Glen Canyon Dam release rates are non-erosive for at least 90 percent of years. The highlighted row provides the percentage of futures that meet this criterion.

Figure TA 5-5
Glen Canyon Dam Releases: Robustness.
Percent of futures in which the sediment year maximum monthly release is less than 900,000 acre-feet in the percent of years specified in each row



Performance under each Alternative

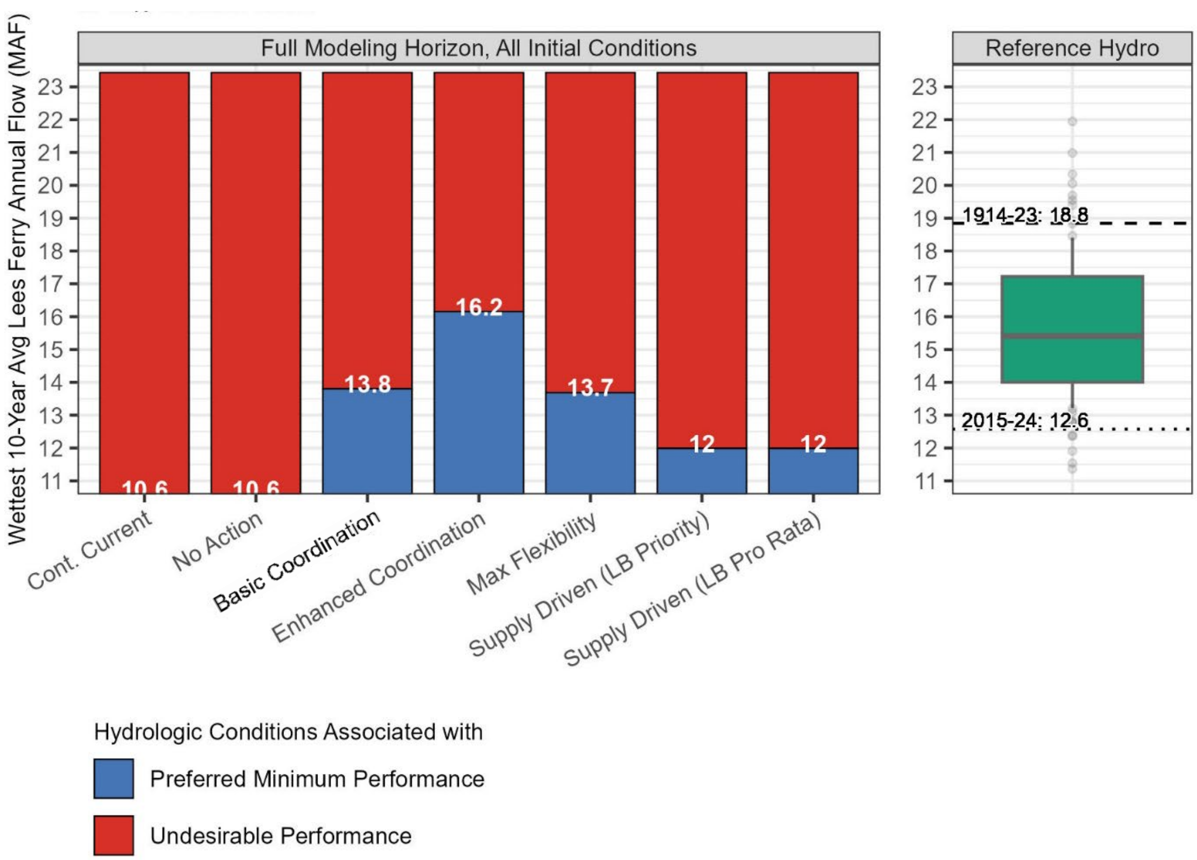
- Under the Enhanced Coordination Alternative, 59 percent of simulated futures meet the preferred minimum performance level over the full modeling period. This alternative is substantially more robust than all other alternatives across all levels of performance.
- Under the Basic Coordination and Maximum Operational Flexibility Alternatives, 28 percent and 20 percent of simulated futures satisfy the preferred minimum performance level, respectively.
- Under the CCS Comparative Baseline, the No Action Alternative, and the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches), less than 10 percent of simulated futures satisfy the preferred minimum performance level.

To a certain extent, release volumes are of reduced concern due to variability throughout the sediment year and flexibility in moving water under LTEMP. If the highest releases happen before most major Paria sediment deliveries in the late summer, sediment will remain in the riverbed for a fall HFE. Under current LTEMP operations, there is flexibility to reduce releases after sediment delivery and store water that can be released during an HFE. Because of those elements, it is anticipated that in most years with reservoir elevations above 3,500 feet and average monthly releases greater than 900,000 af per month, management flexibility will be allowed for the maximum preservation of sand mass.

Figure TA 5-6 shows the streamflow conditions that can be expected to result in more than 10% of years experiencing a maximum monthly release above 900,000 acre-feet (i.e. the undesirable outcome). The average natural flow at Lees Ferry during the wettest 10-year period in each future (shown on the y-axis) was identified as a good predictor of undesirable performance.

The reference hydrology shows the distribution of the wettest 10-year average natural flows for an ensemble of projected conditions (see **Chapter 3, Figure 3-4**, for more information on the selected reference hydrology). The plot also shows important historical context. The wettest 10-year average flow in the historical record occurred from 1914-1923 with a value of 18.8 maf per year. The average of the most recent 10-year period was much drier with an average of 12.6 maf per year.

Figure TA 5-6
Glen Canyon Dam Releases: Vulnerability.
Conditions that could cause the maximum monthly outflow to exceed 900,000 acre-feet in more than 10% of years



Performance under each Alternative

- The Enhanced Coordination Alternative is the least vulnerable to highly erosive flow conditions, being expected to withstand futures with 10-year average flows up to 16.2 maf per year. Comparing this value to the reference hydrology, it is vulnerable to less than 50% of futures.
- The Basic Coordination and Maximum Operational Flexibility Alternatives are the second and third least vulnerable alternatives, being vulnerable to futures that experience 10-year average flows exceeding 13.8 and 13.7 maf per year, respectively. About 75 percent of futures in the reference hydrology experience a 10-year average greater than these values.
- The Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) is vulnerable to futures that experience 10-year average flows exceeding 12.0 maf per year, which occurs in over 90 percent of futures in the reference hydrology.
- The CCS Comparative Baseline and No Action Alternative are the most vulnerable, being vulnerable to futures that experience 10-year average flows exceeding 10.6 maf per year. All futures in the reference hydrology experience a 10-year average exceeding this value.

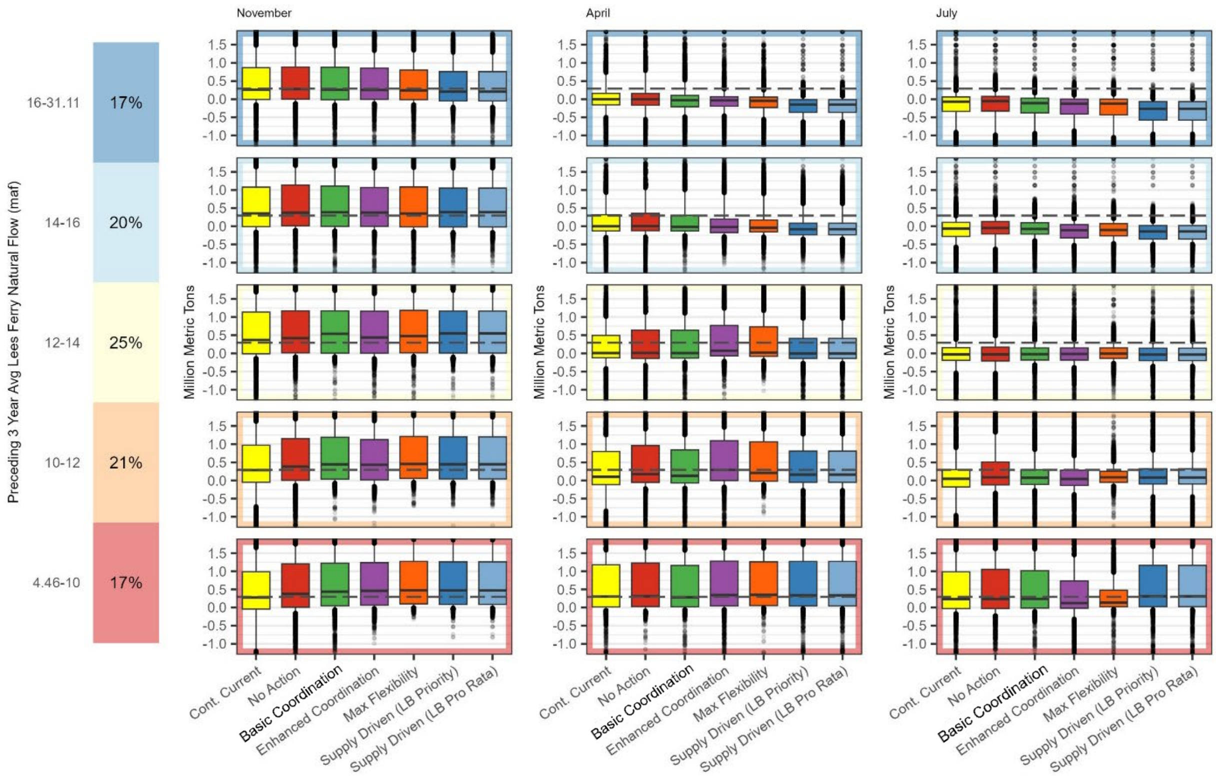
Figure TA 5-7 shows the distribution of sand accumulation (in millions of metric tons) in Marble Canyon for three time periods: July 1 to November 1, July 1 to April 1, and July 1 to July 1 (the full sediment year, Topping et al. [2000]). The distributions are further categorized according to five hydrologic conditions based on the average flow rate at Lees Ferry over the preceding three-year period. A future is considered preferable if the sand mass in Marble Canyon exceeds 294,000 metric tons, indicated by a dashed horizontal line, in November or April at least once every four years. 294,000 metric tons is the average transport capacity for a 60-hour HFE event, the duration at which successful beach building occurs.

Interpretation of **Figure TA 5-7** depends on the three periods of interest. Because most of the sand input from the Paria and Little Colorado Rivers occurs during the summer-fall thunderstorm season of July to November, it is preferable to have as much sand accumulation as possible during this period (to implement a fall HFE). Whether a spring HFE can be implemented is reflected in the level of accumulation from July to April. Because implementation of an HFE in fall or spring will utilize the accumulated sand for sandbar building, annual sand accumulation (represented in the July-to-July period) is not expected. If HFEs are implemented in either fall or spring, the July-to-July accumulation is expected to be near zero.

An inspection of **Figure TA 5-7** reveals the following:

- For all five hydrologic conditions, most sand accumulation occurs from July to November. Slightly less accumulation occurs for the wettest conditions, during which non-HFE releases are more likely to transport sand downstream, while slightly more accumulation occurs for the driest conditions.

Figure TA 5-7
Marble Canyon Sand Accumulation from (left) July 1 to November 1, (middle) July 1 to April 1, and (right) July 1 to July 1



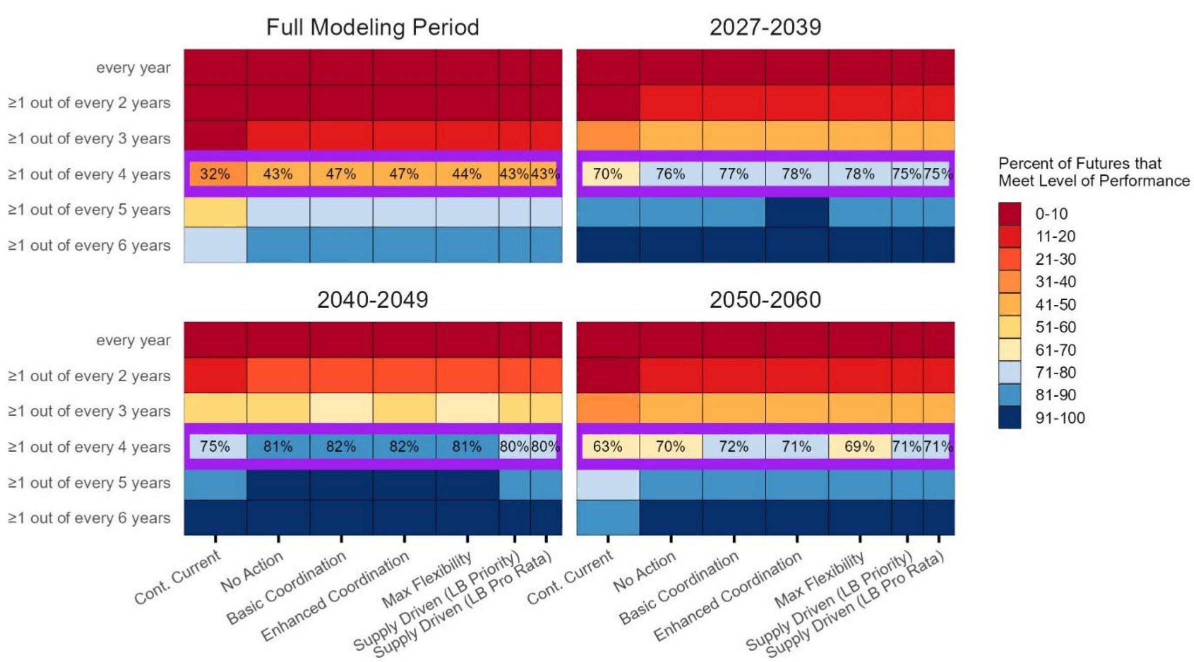
- In the Moderately Wet and Wet Flow Categories (14.0 maf and above), conditions that would trigger an HFE release (i.e., Marble Canyon sand accumulation exceeding 294,000 metric tons) are more likely to occur in November. In addition, larger than normal releases outside of HFE events are likely to contribute to sediment erosion during the fall and winter months. Therefore, there is generally a decrease in sand accumulation between November and April, resulting in a median sand accumulation between July and April of close to zero. Very little change in sand accumulation occurs from April to July, indicating that spring HFEs are uncommon during these conditions.
- In the Average and Dry Flow Categories (10.0 maf to 14.0 maf), there is still a general decrease in sand accumulation between November and April, but the decrease is more gradual. As a result, sand accumulation exceeds 294,000 metric tons for a greater percentage of futures in April, although the median sand accumulation between July and April is still close to zero. The gradual decrease continues to occur between April and July, so that on an annual basis (July 1 to July 1), there is little net change in sand accumulation, similar to the wettest two categories.
- In the Critically Dry Flow Category (4.46–10.0 maf), there is little change in sand accumulation between both November and April, and April and July.

Performance under each Alternative

- Across all hydrologic conditions, all five alternatives perform comparably from July to November, generally resulting in positive sand accumulation.
- For all but the driest conditions, all five alternatives also perform comparably from July to July, resulting in minimal change on an annual basis. The wettest conditions tend to result in slightly less sand accumulation than others.
- For the driest conditions, sand accumulation is generally positive for all five alternatives. The smallest sand accumulation occurs for the Maximum Operational Flexibility Alternative and Enhanced Coordination Alternative (in that order), under which more sand is transported than in other alternatives.

Figure TA 5-8 shows the percentage of futures in which the November or April sand mass in Marble Canyon exceeds 294,000 metric tons in the frequency of years specified in each row. 294,000 metric tons is the average transport capacity for a 60-hour HFE. The highlighted row shows the percent of futures in which this criterion is satisfied at least one year out of every 4, which was chosen as the preferred minimum performance level.

Figure TA 5-8
Marble Canyon Sand Mass: Robustness.
Percent of futures in which the Marble Canyon sand mass exceeds 294,000 metric tons in November or April in the frequency of years specified in each row



Performance under each Alternative

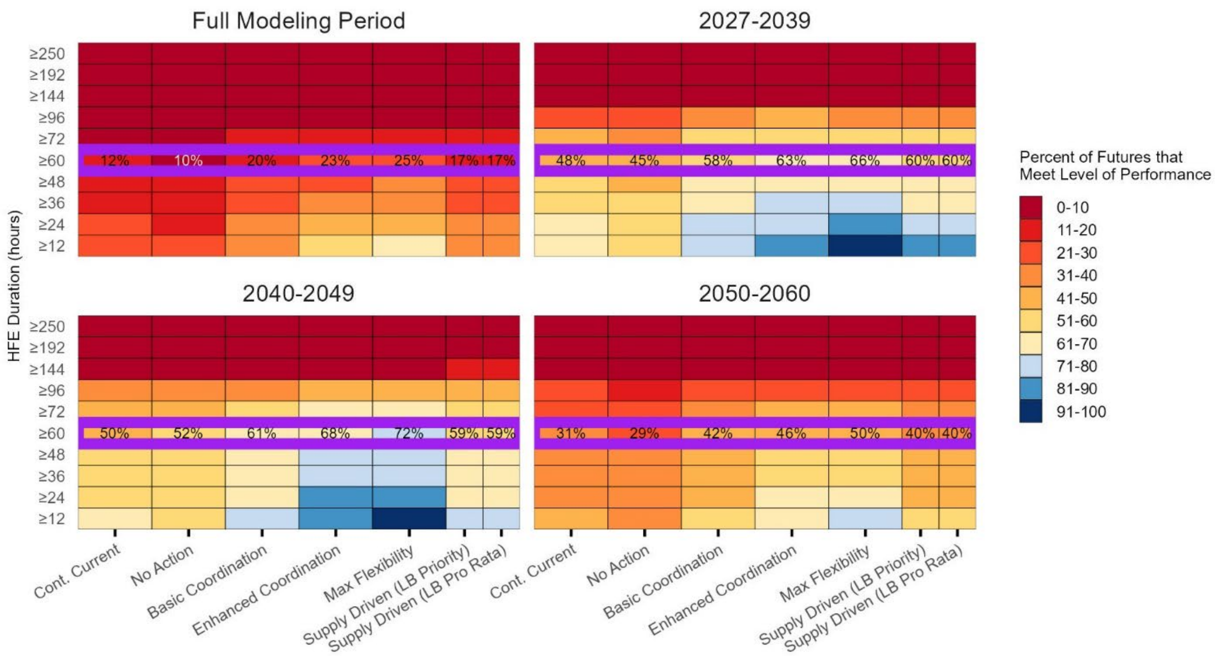
- Aside from the CCS Comparative Baseline, the percentage of futures in which November or April sand mass exceeds 294,000 metric tons at least every four years is comparable across the alternatives, ranging from 43 percent to 47 percent for the full modeling period.
- For the CCS Comparative Baseline, less than a third of the futures in the full modeling period meet the 294,000 metric ton threshold at least once every four years.
- All alternatives perform better for the subperiods than they do for the full modeling period, suggesting that some of the futures meet the preferred minimum performance level in one subperiod but not all subperiods, reflecting the variability of interdecadal hydrologic conditions and their impact on performance.

TA 5.2.4 Issue 3: HFE Frequency and Duration

Water availability in, and water releases from, Lake Powell can have an impact on HFE scheduling. Large non-HFE releases, such as the equalization flows implemented in 2011 to balance storage between Lake Powell and Lake Mead (Hazel et al. 2022), can reduce the sand mass in Marble Canyon available for an HFE without providing the benefit of increasing sandbar volumes further downstream (Grams et al. 2025; Topping et al. 2021; Salter et al. 2025). Since the alternatives propose different ways of operating Glen Canyon Dam, they have different impacts on water availability in Lake Powell, and consequently, the scheduling of HFE releases. Grams et al. (2025) noted that, except for the HFE implemented on March 26, 1996, the durations for all HFEs implemented were between 60 and 96 hours and demonstrated that modeled durations below 60 hours have lower predicted sandbar volumes.

Figure TA 5-9 shows the percentage of futures in which the annual HFE duration is the number of hours specified in each row at least once every four years. To allow for sandbar deposition that is sufficient to at least partially compensate for natural erosion in between HFEs, a future is considered to satisfy the preferred minimum performance level if a spring or fall HFE of 60 hours or longer occurs at least once every four years, as indicated by the highlighted row.

Figure TA 5-9
Annual HFE Duration: Robustness.
Percent of futures in which the annual HFE duration is the number of hours specified in each row at least once every four years

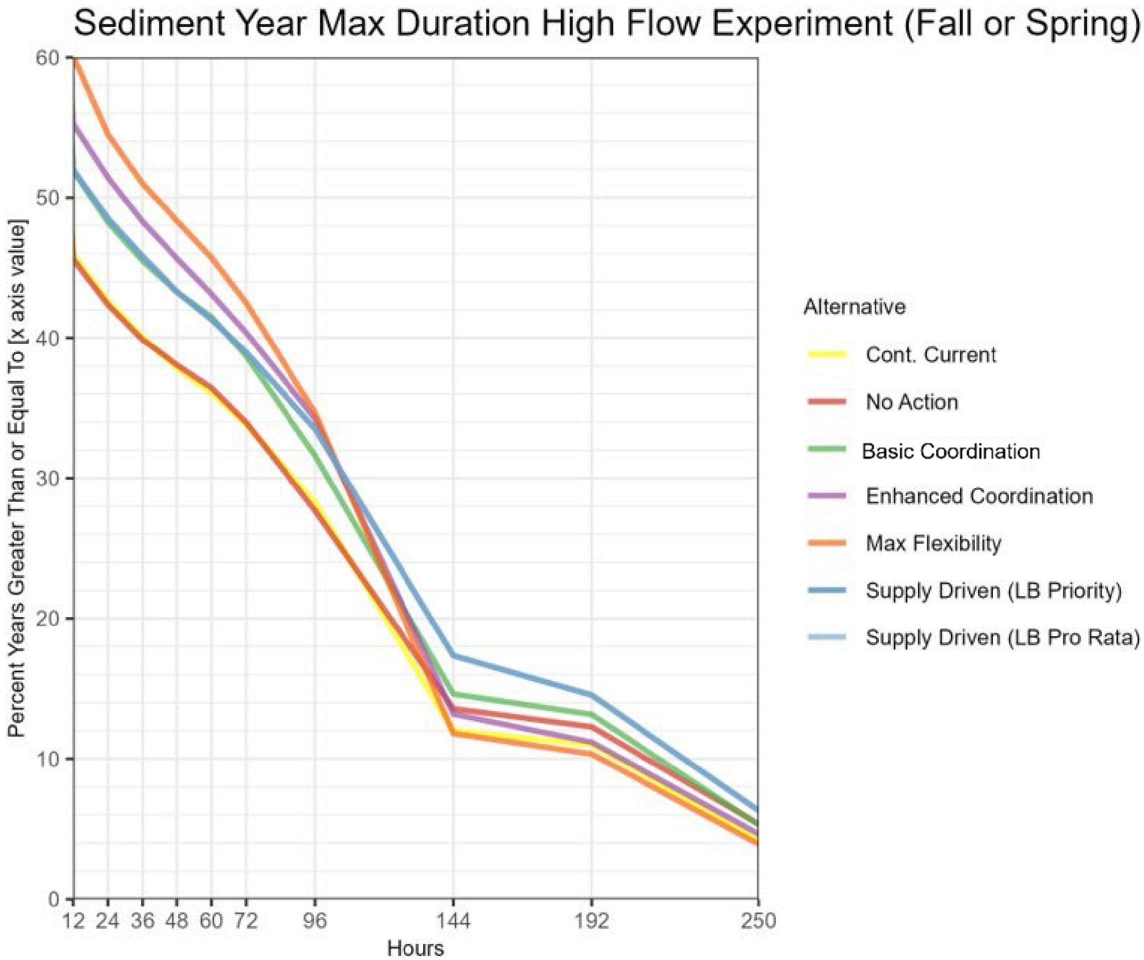


Performance under each Alternative

- For the full modeling period, none of the alternatives satisfy the minimum preferred performance level in more than 30% of futures, indicating none of the alternatives are robust with respect to HFEs of at least 60 hours occurring at least once every four years.
- The percentage of futures meeting the preferred minimum performance level in each subperiod is notably higher than the full modeling period, indicating the performance criterion is often satisfied in one subperiod but failed in another.
- For all periods, action alternatives are more robust than the CCS Comparative Baseline and No Action Alternative, with the Maximum Operational Flexibility Alternative performing slightly better than the others.

Figure TA 5-10 shows the frequency of HFE releases as a function of HFE duration, represented as the percentage of simulated years in which an HFE of a specified duration occurs. A future is considered preferable if an HFE lasting 60 hours or longer occurs at least once every four years. While **Figure TA 5-10** does not directly address this indicator, it suggests the likelihood with which it is met.

Figure TA 5-10
Frequency of HFE Releases as a Function of HFE Duration



Performance under each Alternative

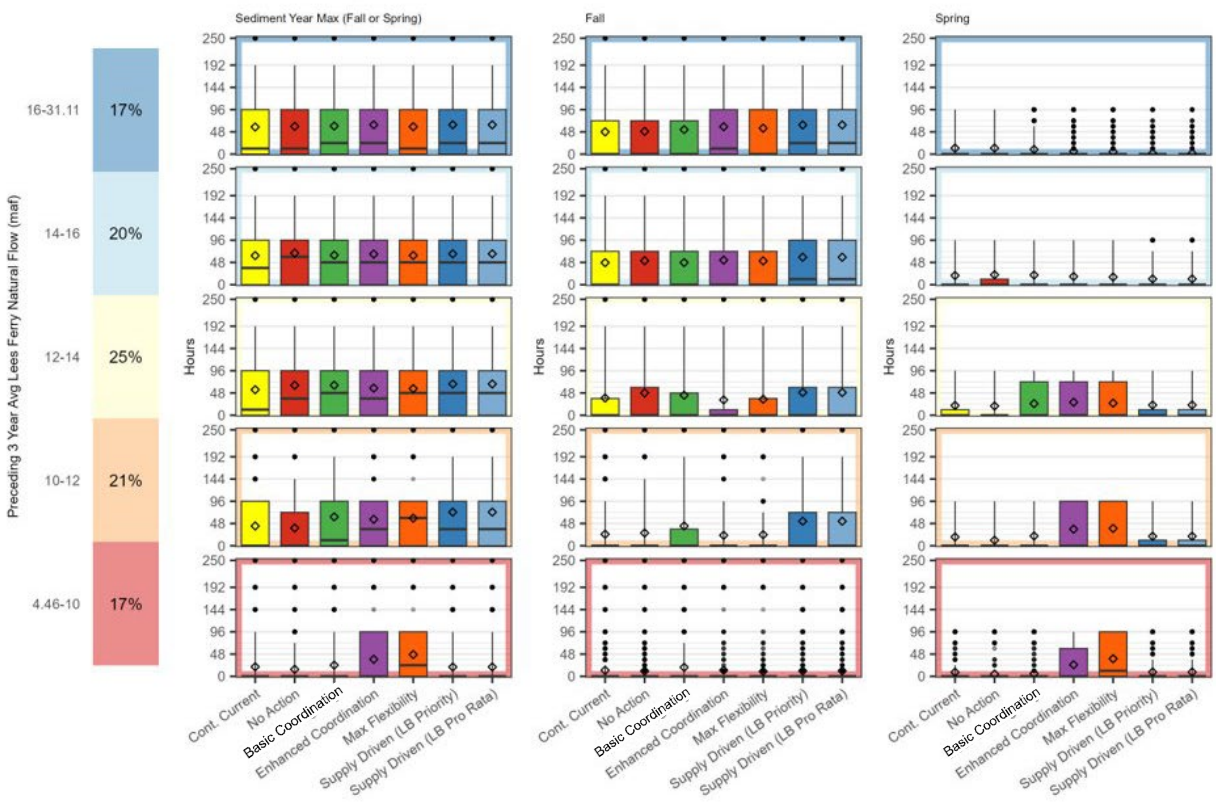
- For HFE releases lasting 12 to 96 hours, the Enhanced Coordination and Maximum Operational Flexibility Alternatives perform the best, with 46 and 43 percent of years having HFE releases greater than or equal to 60 hours, respectively.
- For HFE releases greater than or equal to 96 hours, the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) perform better than the other alternatives.
- Below 60 hours, the performance of the Basic Coordination Alternative is generally comparable to that of the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) and lower than the other action alternatives.

The worst performance generally occurs under the CCS Comparative Baseline and the No Action Alternative. Their performance is comparable for HFE durations below 144 hours. For HFE durations above 144 hours, the No Action Alternative performs slightly better than the CCS Comparative Baseline. However, excluding the HFE implemented on March 26, 1996, HFE durations above 144 hours have not been implemented (Grams et al. 2025).

- While **Figure TA 5-9** indicates that, across all alternatives, 60-hour HFEs would occur in 36 to 46 percent of years simulated, **Figure TA 5-8** indicates 60-hour HFEs every four years would occur in only 10 to 25 percent of futures. This likely indicates that many more futures have HFEs concentrated over a small time period than futures in which HFEs are evenly spread out, another reflection of the importance of interdecadal hydrologic variability.

Figure TA 5-11 shows the distribution of HFE durations for the full sediment year (July 1 to July 1), fall, and spring. The distributions are further categorized according to five hydrologic conditions based on the average flow rate at Lees Ferry over the preceding three-year period. A future is considered preferable if an HFE lasting 60 hours or longer occurs at least once every four years. While **Figure TA 5-11** does not directly address this indicator, it provides some indication of the likelihood with which it is met.

Figure TA 5-11
Annual Duration of HFE Releases



Performance under each Alternative

- For the Critically Dry Flow Category (4.46–10.0 maf), only the Maximum Operational Flexibility and Enhanced Coordination Alternatives result in HFE durations of any significant duration, typically occurring in the spring.
- For the Dry Flow Category (10.0–12.0 maf), all alternatives except for the No Action Alternative perform comparably across the full sediment year, but the timing of their HFEs varies by alternative.

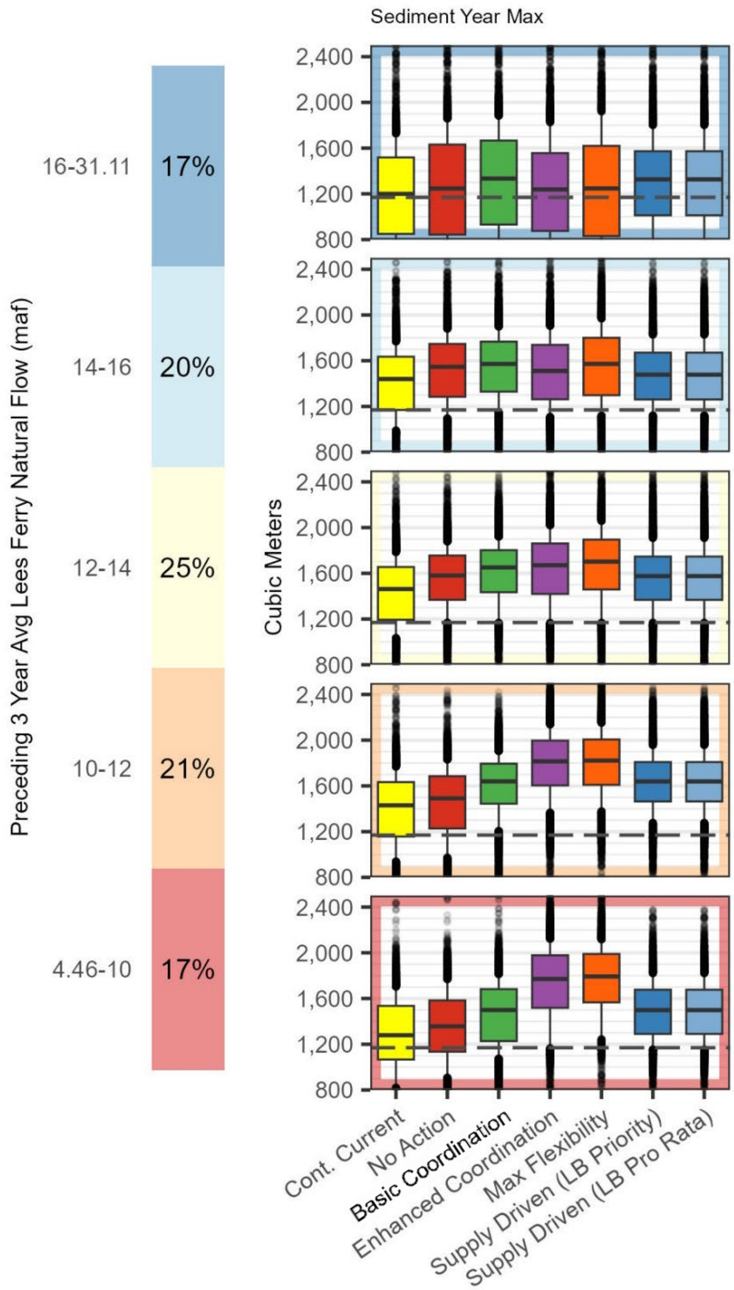
- For the Average Flow Category (12.0–14.0 maf), HFE durations are as long or longer than their corresponding durations in fall or spring. This indicates that spring and fall HFEs could occur in different sediment years, making their effects cumulative rather than concurrent.
- HFEs under the Basic Coordination, Enhanced Coordination, and Maximum Operational Flexibility Alternatives are more likely to occur in the spring, while HFEs under the other alternatives are more likely to occur in the fall.
- For the three wettest categories (Average, Moderately Wet and Wet Flow Categories) (12.0 maf and above), the distribution of annual HFE durations over the full sediment year is comparable across all alternatives.
- For the Wet and Moderately Wet Flow Categories (14.0 maf and above), fall HFE duration is slightly longer for the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) than the others. Spring HFE durations are rare for all five alternatives and the CCS Comparative Baseline.
- As the preceding three-year average flow decreases (becomes drier), both the Enhanced Coordination and Maximum Operational Flexibility Alternatives show a shift from fall HFE releases to spring HFE releases.

TA 5.2.5 Issue 4: Sandbar Volume

Sandbars enhance environmental habitat and recreation opportunities and protect archaeological resources. Therefore, a larger sandbar volume is considered to have a positive impact. In the context of sediment, the ultimate measure of an alternative's performance is the volume of "usable" sand in the canyon; that is, the sandbar volume above the water level during a 25,000 cfs flow condition, the threshold above which camping and recreational activities are considered safe.

Figure TA 5-12 shows the distribution of sandbar volume above the water level associated with a flow rate of 25,000 cfs, considered the threshold to provide safety from flooding for recreational purposes. The distributions are further categorized according to five hydrologic conditions based on the average flow rate at Lees Ferry over the preceding three-year period. A future is considered preferable if sandbar volume exceeds the threshold at the start of the simulation period for at least 60 percent of the years within that period. The sandbar volume at the start of the simulation period is 1169.512 cubic meters, indicated by a dashed horizontal line.

Figure TA 5-12
Sandbar volume above the water level associated with a flow rate of 25,000 cfs



Performance under each Alternative

- For all but the Wet Flow Category, all alternatives show sandbar growth in greater than 60 percent of years, with all but the CCS Comparative Baseline and No Action Alternative in the Critically Dry Flow Category showing sandbar growth in greater than 75 percent of years.
- For the Wet Flow Category, only the Basic Coordination and the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) show sandbar growth in greater than 60 percent of years, whereas median sandbar volume is lowest for the CCS Comparative Baseline, and 25^{th} percentile sandbar volumes the CCS Comparative Baseline, No Action Alternative, and Maximum Operational Flexibility Alternative are 40 percent to 50 percent lower than the initial condition.
- In general, sandbar growth increases as hydrologic conditions become drier. Differences in performance among the alternatives also increase as hydrologic conditions become drier. For the Critically Dry Flow Category, the Enhanced Coordination and Maximum Operational Flexibility Alternatives clearly perform the best.

Figure TA 5-13 shows the percentage of futures with *net* sandbar growth by comparing the maximum sandbar volume for each year with the volume at the start of each of four periods (2027–2039, 2040–2049, 2050–2060, and 2027–2060). It is important to note that the figure does not show the percentage of years with year-over-year sandbar growth; it is very possible for sandbar volume to be lower than it was the year before and still be higher than it was at the start of the period. The figure reflects an alternative's ability to achieve long-term sandbar growth over scales of decades or more.

A future is considered to satisfy the minimum preferred performance level if at least 60 percent of years within a given period have a sandbar volume that is larger than the sandbar volume at the start of the given period. The highlighted row provides the percentage of futures that meet this criterion.

Performance under each Alternative

- All alternatives perform similarly, with Maximum Operational Flexibility (93 percent), Enhanced Coordination (92 percent) and Supply Driven (93 percent for both versions) Alternatives performing best over the full modeling period.
- The percentage of futures that satisfy the preferred minimum performance level is lowest among the CCS Comparative Baseline, No Action Alternative, and Basic Coordination Alternative, in that order.
- For all alternatives, most of the increase occurs in the first 13-year period, after which sandbar growth slows. Since **Figure TA 5-13** defines growth as sandbar volumes larger than they were at the start of a period, this may explain why, for the full simulation period, it indicates sandbar growth above 90 percent for all five action alternatives when the percentage of futures with 60-hour HFEs at least once every four years is at most 25 percent (**Figure TA 5-9**). If the initial growth in sandbars is large enough, relatively small decreases in sandbar volumes in subsequent years could still result in sandbar volumes larger than they were at the start of the simulation period.

Figure TA 5-13
Long-Term Sandbar Growth: Robustness.
Percent of futures in which the weighted average sandbar volume of Grand Canyon and Marble canyon has increased relative to the start of each modeling period in the percent of years specified in each row

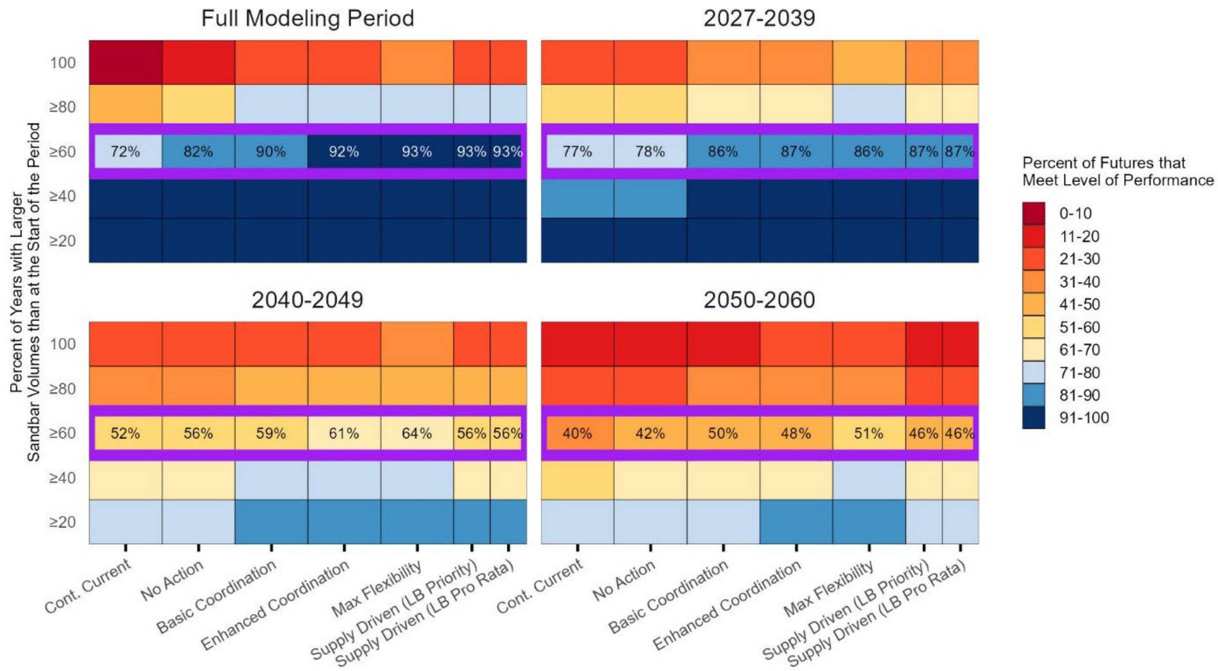
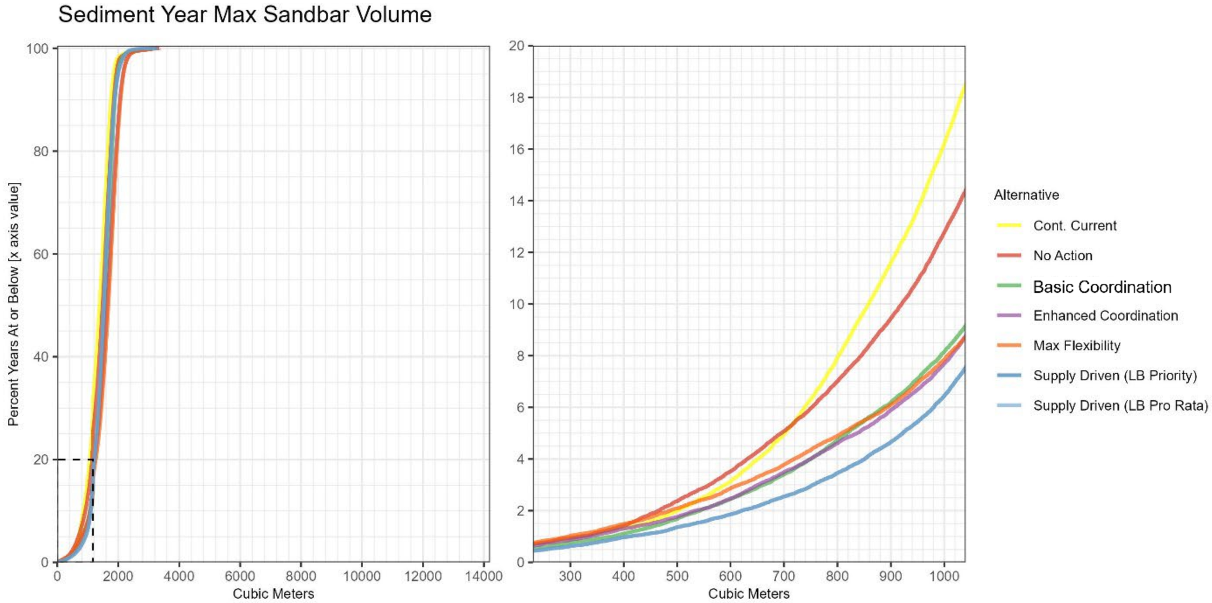


Figure TA 5-14 shows the percentage of simulated years for which the maximum sandbar volume is less than or equal to a given value. A lower percentage of years for which sandbar volume is below a given value corresponds to a greater percentage of years for which sandbar volume is above that value. Therefore, curves with lower placement in the plot imply better performance for that alternative.

Figure TA 5-14
Percentage of Years for which Maximum Sandbar Volume is at or below Given Values



Performance under each Alternative

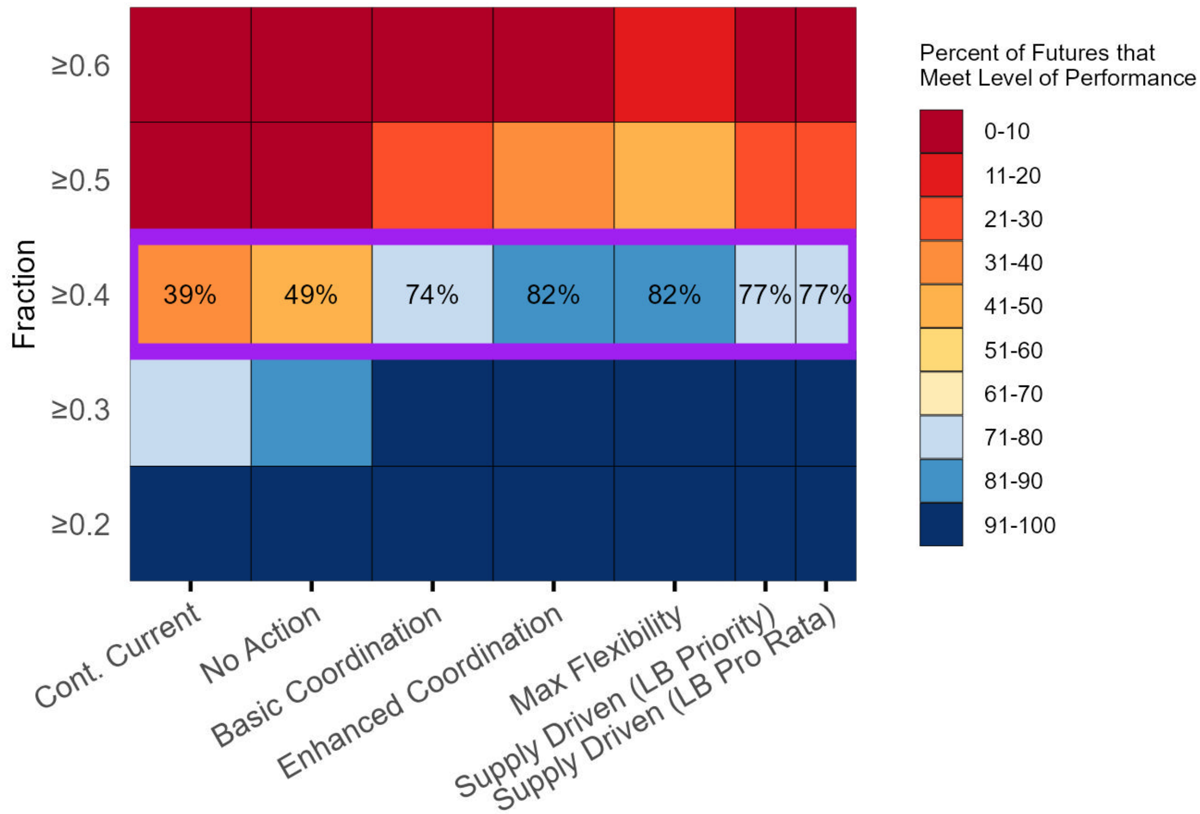
- The Supply Driven Alternative (both LB Priority and LB Pro Rata approaches), represented by the blue curve, results in the best performance in the context of this plot.
- Performance among the Basic Coordination, Enhanced Coordination, and Maximum Operational Flexibility Alternatives are comparable and rank second.
- Performance under the No Action Alternative ranks third, with performance for the CCS Comparative Baseline ranking last.

TA 5.2.6 Issue 5: Sand Transport

While sand can be transported downstream with flows well below 37,000 cfs, these lower flows are not as conducive to sandbar formation and retention. The higher the fraction of sand transported during the larger flow events (above 37,000 cfs), the more sand will be available for sandbar formation (Hazel et al. 2022; Salter 2025).

Figure TA 5-15 shows the percentage of futures in which the total sand mass transported by flow rates above 37,000 cfs (sandbar-forming flow rates) exceed a given fraction over the 34-year simulation period. A future is considered to meet the minimum preferred performance level if the fraction of sand mass transported by sandbar-forming flow rates is at least 0.4 (40 percent of the sand transport). The highlighted row provides the percentage of futures that meet this criterion.

Figure TA 5-15
Sand Load Index: Robustness.
Percent of futures in which the sand mass transported when flows are above 37,000 cfs is at least the fraction specified in each row of the total sand mass transported over the 34-year modeling period



Performance under each Alternative

- Under the Maximum Operational Flexibility and Enhanced Coordination Alternatives, 82 percent of simulated futures satisfy the minimum preferred performance level. That is, at least 40 percent of sand mass is transported by sandbar-forming flow rates in 82 percent of simulated futures for these two alternatives.
- The next best performance occurs under the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches), for which 77 percent of futures meet the preferred minimum performance level, followed by the Basic Coordination Alternative, for which 74 percent of futures meet the preferred minimum performance level.
- Under both the No Action Alternative and the CCS Comparative Baseline, at least 40 percent of sand mass is transported by sandbar-forming flow rates in less than half of the simulated futures, with the CCS Comparative Baseline performing the worst of all alternatives.

TA 5.3 References

Bureau of Reclamation (Reclamation). 1995. Operation of Glen Canyon Dam: Colorado River Storage Project, Arizona, Final Environmental Impact Statement. Upper Colorado Region, Salt Lake City, Utah. Internet website: https://www.usbr.gov/uc/envdocs/eis/gc/pdfs/Cov-con/cov-con.pdf.

_____. 2016. Glen Canyon Dam Long-Term Experimental and Management Plan Final Environmental Impact Statement. Upper Colorado Region, Salt Lake City, Utah, and National Park Service, Intermountain Region, Lakewood, Colorado. Internet website: https://ltempeis.anl.gov/documents/final-eis/.

_____. 2024. Glen Canyon Dam Long-Term Experimental and Management Plan–Final Supplemental Environmental Impact Statement. U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado River Basins, Salt Lake City, Utah. Internet website: http://www.riversimulator.org/2025Guidelines/USBR/Bass/Final/GCDltempSEISFinal2024USBR.pdf.

Collins, B. D., D. R. Bedford, S. C. Corbett, C. Cronkite-Ratcliff, and H. C. Fairley. 2016. Relations between rainfall–runoff-induced erosion and aeolian deposition at archaeological sites in a semi-arid dam-controlled river corridor. *Earth Surface Processes and Landforms,* 41(7), 899–917.

East, A. E., B. D. Collins, J. B. Sankey, and S. C. Corbett. 2016. Conditions and Processes Affecting Sand Resources at Archeological Sites in the Colorado River Corridor below Glen Canyon Dam, Arizona. U.S. Geological Survey Professional Paper 1825. Internet website: https://doi.org/10.3133/pp1825.

Grams, P. E., J. C. Schmidt, and D. J. Topping. 2007. "The rate and pattern of bed incision and bank adjustment on the Colorado River in Glen Canyon downstream from Glen Canyon Dam, 1956–2000." *Geological Society of America Bulletin* 119(5-6):556–575.

Grams, P. E., J. C. Schmidt, and M. E. Andersen. 2010. 2008 High-Flow Experiment at Glen Canyon Dam—Morphologic Response of Eddy-Deposited Sandbars and Associated Aquatic Backwater Habitats along the Colorado River in Grand Canyon National Park. Open-File Report 2010-1032. US Geological Survey, Grand Canyon Monitoring and Research Center, Flagstaff, Arizona.

Grams, P. E., D. J. Topping, J. C. Schmidt, J. E. Hazel Jr., and M. Kaplinski. 2013. "Linking morphodynamic response with sediment mass balance on the Colorado River in Marble Canyon: Issues of scale, geomorphic setting, and sampling design." *Journal of Geophysical Research: Earth Surface* 118(2):361–381.

Grams, P. E., D. J. Topping, G. Salter, K. A. Chapman, R. B. Tusso, and E. R. Mueller. 2025. "Implementation of controlled floods for sediment management on the Colorado River in Grand Canyon under aridification." *River Research and Applications* 41:334–348.

Griffiths, R. E., and D. J. Topping. 2017. "Importance of measuring discharge and sediment transport in lesser tributaries when closing sediment budgets." *Geomorphology* 296:59–73.

Hazel, J. E., Jr.; M. A. Kaplinski; D. Hamill; D. Buscombe; E. R. Mueller; R. P. Ross; K. Kohl; et al. 2022. Multi-decadal sandbar response to flow management downstream from a large dam. In The Glen Canyon Dam on the Colorado River in Marble and Grand Canyons, Arizona. US Geological Survey Professional Paper 1873, US Geological Survey, Reston, Virginia.

Mueller, E. R., and P. E. Grams. 2021. "A morphodynamic model to evaluate long-term sandbar rebuilding using controlled floods in the Grand Canyon." *Geophysical Research Letters* 48(9):1–10.

Mueller, E. R., P. E. Grams, J. E. Hazel Jr., and J. C. Schmidt. 2018. "Variability in eddy sandbar dynamics during two decades of controlled flooding of the Colorado River in the Grand Canyon." *Sedimentary Geology* 363:181–199.

Rubin, D. M., D. Buscombe, S. A. Wright, D. J. Topping, P. E. Grams, J. C. Schmidt, J. E. Hazel, Jr., et al. 2020. "Causes of variability in suspended-sand concentration evaluated using measurements in the Colorado River in Grand Canyon." *Journal of Geophysical Research: Earth Surface* 125(9).

Rubin, D. M., D. J. Topping, J. C. Schmidt, J. Hazel, M. Kaplinski, and T. S. Melis. 2002. "Recent sediment studies refute GCD hypothesis." *EOS, Transactions of the American Geophysical Union* 83(25):273, 277–278.

Rubin, D. M., J. M. Nelson, and D. J. Topping. 1998. "Relation of inversely graded deposits to suspended-sediment grain-size evolution during the 1996 flood experiment in Grand Canyon." *Geology* 26(2):99–102.

Salter, G., Topping, D. J., Wang, J., Schmidt, J. C., Yackulic, C. B., Bair, L. S., et al. 2025. "Reservoir Operational Strategies for Sustainable Sand Management in the Colorado River." Water Resources Research 61, e2024WR038315.

Sankey, J. B. and A. E. Draut. 2014. "Gully annealing by aeolian sediment: field and remote-sensing investigation of aeolian–hillslope–fluvial interactions, Colorado River corridor, Arizona, USA." *Geomorphology,* 220, 68–80.

Sankey, J. B., A. East, J. Caster, H. Fairley, J. Dierker, E. Brennan, L. Pilkington, et al. 2023a. Aeolian and Drainage Classification Data for Various Archaeological Sites in Grand Canyon National Park along the Colorado River from 1973 to 2022. US Geological Survey data release, May 15, 2023. Internet website: https://doi.org/10.5066/P9X9ZDPK.

______. 2023b. "Archaeological sites in Grand Canyon National Park along the Colorado River are eroding owing to six decades of Glen Canyon Dam operations." Journal of Environmental Management 342(118036): 1–17. Internet website: https://doi.org/10.1016/j.jenvman.2023.118036.

Schmidt, J. C., and D. M. Rubin. 1995. "Regulated Streamflow, Fine-Grained Deposits, and Effective Discharge in Canyons with Abundant Debris Fans," pp. 177–195 in Natural and Anthropogenic Influences in Fluvial Geomorphology (J. E. Costa, A. J. Miller, K. W Potter, and P. R. Wilcock, editors). Geophysical Monograph, American Geophysical Union.

Topping, D. J., D. M. Rubin, and L. E. Vierra Jr. 2000. "Colorado River sediment transport: Part 1: Natural sediment supply limitation and the influence of the GCD." *Water Resources Research* 36:515–542.

Topping, D. J., P. E. Grams, R. E. Griffiths, D. J. Dean, S. A. Wright, and J. A. Unema. 2021. "Self-limitation of sand storage in a bedrock-canyon river arising from the interaction of flow and grain size." *Journal of Geophysical Research: Earth Surface* 126: e2020JF005565.

United States Geological Survey (USGS). 2011. Effects of Three High-flow Experiments on the Colorado River Ecosystem Downstream from GCD, Arizona, US Geological Survey Circular 1366. Internet website: https://pubs.usgs.gov/circ/1366/.

_____. 2024. Discharge, Sediment, and Water Quality Monitoring Data, Grand Canyon Monitoring and Research Center. Internet website: https://www.gcmrc.gov/discharge_qw_sediment/.

Van Steeter, M. M. and Pitlick, J. 1998. "Geomorphology and endangered fish habitats of the upper Colorado River: 1. Historic changes in streamflow, sediment load, and channel morphology." *Water Resources Research* 35(2):287–302.

Voichick, N. and D. J. Topping. 2014. Extending the Turbidity Record—Making Additional Use of Continuous Data from Turbidity, Acoustic-Doppler, and Laser Diffraction Instruments and Suspended-Sediment Samples in the Colorado River in Grand Canyon. Scientific Investigations Report 2014—5097. US Geological Survey, Reston, Virginia.

Webb, R. H., and P. G. Griffiths. 2001. Monitoring of Coarse Sediment Inputs to the Colorado River in Grand Canyon, US Geological Survey Fact Sheet 019-01. February. Internet website: http://pubs.usgs.gov/fs/FS-019-01/pdf/fs-019-01.pdf.

Wright, S. A., C. R. Anderson, and N. Voichick. 2008. "A simplified water temperature model for the Colorado River below Glen Canyon Dam." *River Research and Applications* 25(6):675–686.

Wright, S. A., D. J. Topping, D. M. Rubin, and T. S. Melis. 2010. "An approach for modeling sediment budgets in supply-limited rivers." *Water Resources Research* 46(10):1–18.

Zagona, E.A., T. J. Fulp, R. Shane, T. Magee, and H. M. Goranflo. 2001. "Riverware: A generalized tool for complex reservoir system modeling" *Journal of the American Water Resources Association* 37:913-929. Internet website: https://doi.org/10.1111/j.1752-1688.2001.tb05522.x.