Technical Appendix 5

Geomorphology and Sediment

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Acronyms and Abbreviations

Acronym or Abbreviation	Full Phrase
CCS	Continued Current Strategies
cfs	cubic feet per second
DMDU	Decision Making under Deep Uncertainty
HFE	high-flow experiment
kaf	thousand acre-feet
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
USGS	United States Geological Survey

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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) at higher elevations (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, under which high flow pulses increase velocity and shear stress (Wright et al. 2008).

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

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 et al. 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 (RM)

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

30 together contribute roughly 10 percent of the sand annually supplied by the Paria River (Griffiths and Topping 2017). Downstream from RM 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 (see **TA 5.1.4**) 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 the deposition of sediments.

TA 5.1.4 Geomorphic Features

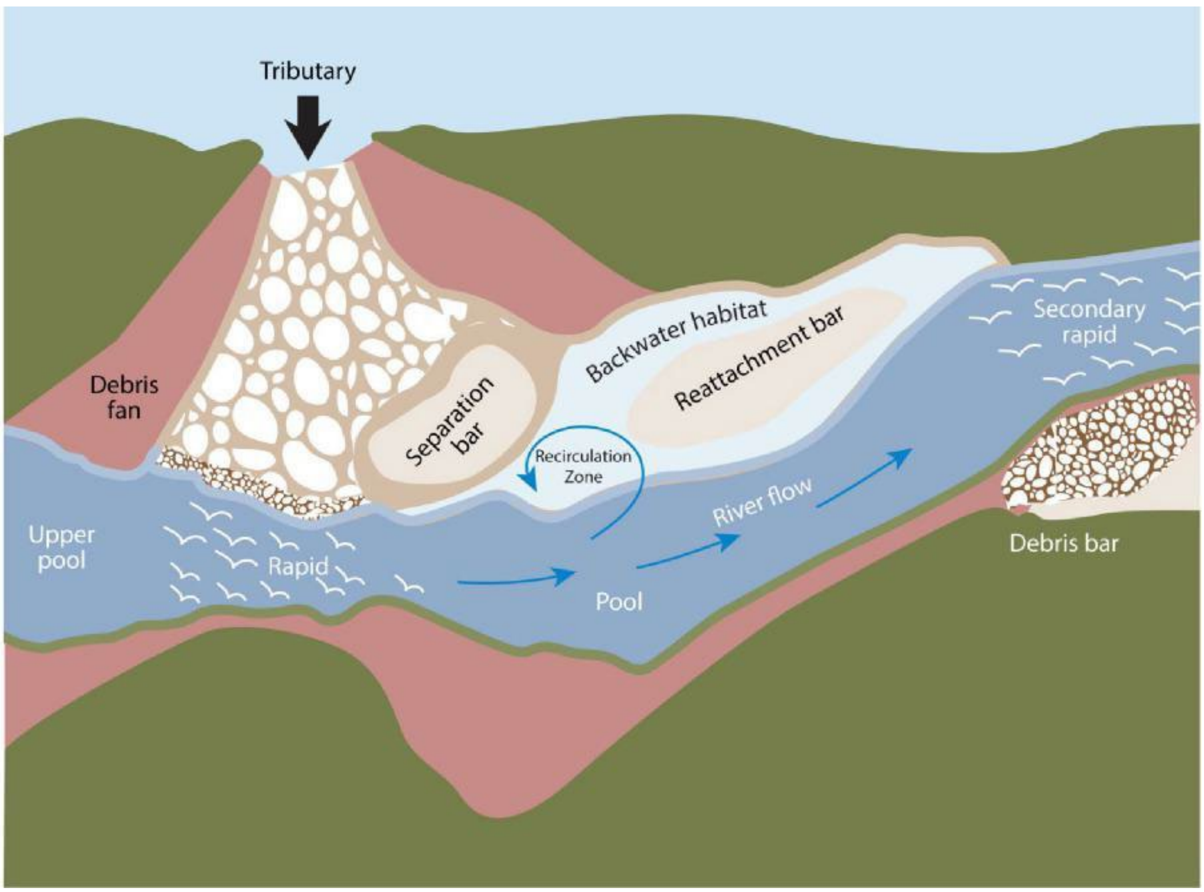
The longitudinal profile of the Colorado River consists of long, flat pool reaches with intermixed short, steep rapids. The rapids in fan-eddy complexes are typically associated with boulder rich deposits formed by tributary debris flows,[4] and flash floods. Debris fans continue to be replenished and 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, 2023b). In addition, beaches provide some of the only camping areas for whitewater river trips, a significant driver of economic activity in the region.

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, it more closely reflects pre-dam conditions of the river and may therefore benefit native fish (see **TA 8**). Turbidity in the Colorado River is a natural condition and is not considered further 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. Lake Powell has sufficient dead storage capacity to trap most incoming sediments, with only a small amount reaching areas near Glen Canyon Dam. Surveys show Lake Powell has lost approximately 13 percent of its designed dead storage capacity (Root and Jones 2022), so sedimentation is not projected to impact dam safety, power generation, or the sediment concentration at Glen Canyon Dam during the analysis timeframe of this environmental impact statement (EIS).

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.

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

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 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 United States Geological Survey (USGS) Grand Canyon Monitoring and Research Center (Grams et al. 2025; Salter et al. 2025), using a sand routing model (Wright et al. 2010) and a 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 see 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 USGS 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. USGS 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, and each alternative was run for all 400 traces (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 Final EIS 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.

This technical appendix uses modeled sand transport, sandbar volumes, and reservoir operations data for the Colorado River in Grand Canyon from the USGS Grand Canyon Monitoring and Research Center (Salter and Grams 2026).

Refer to **Section 3.2**, Analysis Methods, for additional information on Decision Making Under Deep Uncertainty (DMDU) and **Appendix E**, DMDU Overview and Approach, for an overview of how to interpret the DMDU conditional box plots, robustness heat maps, and vulnerability bar plots.

Impact Analysis Area

The impact analysis area used for the USGS Grand Canyon Monitoring and Research Center's 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 Gaging Station (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 mouth of the reservoir, resulting in sediment redistribution that forms new bars and alters the reservoir's 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. Impacts on water surface elevations and consequently erosion and deposition patterns in the delta region of Lake Powell may also result. Sediment redistribution within the reservoirs is not evaluated in this EIS due to the absence of an applicable model.

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 introduce new sources of sediment, 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 EIS 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.
- Reclamation's future operations will remain responsive to hydrology, system conditions, and applicable legal and operational requirements. Reclamation will continue to follow the 2016 Glen Canyon Dam LTEMP EIS and the 2024 LTEMP Supplemental EIS guidelines, which include the planning and implementation team process that helps assess monthly release volumes and Secretarial decision-making.
- 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 and Rubin 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 LTEMP EIS and 2024 LTEMP Supplemental EIS.
- Sandbar volume modeling uses the assumption that HFEs are implemented as often as possible.
- 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 rate of 37,000 cfs, generally considered the flow rate needed for significant deposition on certain sandbar types (Hazel et al. 2022). A 37,000 cfs release requires Lake Powell to be at or above 3,500 feet in April or November, when HFEs are typically scheduled. 3,500 feet also provides a 10-foot buffer above 3,490 feet – the elevation below which water can only be released through the river outlet works. As described in **Chapter 1**, **Section 1.8.4.1**, there are infrastructure concerns associated with the uncertainty of extended operations through the river outlet works as the sole means of sustained water releases from Glen Canyon Dam that could compromise the reliability and operational flexibility of Glen Canyon Dam and affect the ability to meet critical downstream water supply needs 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 a Lake Powell elevation of 3,500 feet. Historically, the lowest elevation at which an HFE has been implemented was 3,523 feet in April 2023, when a large snowpack resulted in predictions of high rates of spring/summer runoff. Fall HFEs have not been implemented when Lake Powell water levels were below 3,590 feet.

Since the models used an elevation of 3,500 feet 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 below the historical low of 3,523 feet, including a high of 18.5 percent under the Supply Driven Alternative (both Priority and Pro Rata approaches). Notably, the two alternatives resulting in the fewest modeled HFEs below 3,523 feet –Enhanced Coordination and Maximum Operational Flexibility – result in the best overall performance with respect to geomorphology and sediment out of all the alternatives, as described in the remainder of this section.

Figure TA 5-2 below depicts the ability of each alternative to maintain a Lake Powell pool elevation greater than 3,500 feet in November or April in the specified percent of years. The preferred minimum performance is shown in the purple highlighted row, which represents the percentage of futures that an alternative exceeds 3,500 feet in November or April in 100 percent of years. The 3,500-foot threshold was selected because it is undesirable to ever miss the opportunity to take advantage of other favorable conditions, such as large sediment loads from the Paria River.

Over the full modeling period, the Maximum Operational Flexibility Alternative is the most robust, as it met the preferred minimum performance in more than 91 percent of futures, followed by the Enhanced Coordination Alternative at 83 percent. The Representative Preferred Alternative meets the preferred minimum performance in 40 percent of futures. The Continued Current Strategies (CCS) Comparative Baseline, as well as Supply Driven (both Lower Basin Priority [LB Priority] and Lower Basin Pro Rata [LB Pro Rata] approaches) and Basic Coordination Alternatives, are less robust, with less than 30 percent of futures meeting the preferred minimum performance. The No Action Alternative is the least robust, with only 13 percent of futures meeting the preferred minimum performance. For all alternatives, fewer futures meet the preferred minimum performance over the full modeling period than in any subperiod. This reflects the increasing difficulty of sustaining a given level of performance over longer periods of time. Only a fraction of the futures meeting the preferred minimum performance in one subperiod also meet the preferred minimum performance in all subperiods, evidence of the interdecadal variability inherent in the ensemble of projected conditions.

Based on the planned length of this decision, it is important to compare robustness in the 2027-2039 modeling period. The Maximum Operational Flexibility (97 percent) and Enhanced Coordination (88 percent) are the most robust alternatives, followed by the Representative Preferred (60 percent). The No Action Alternative (19 percent) is the least robust, and the CCS Comparative Baseline (35 percent), Basic Coordination Alternative (36 percent), and the Supply Driven (both LB Priority and Pro Rata approaches) Alternative (46 percent) perform in the middle.

Table TA 5-1
Percentage of Modeled HFEs Above or Below the Historical 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
CCS Comparative Baseline	6,501	23.9%	85.3%	14.7%	0.41	0.48
No Action Alternative	6,478	23.9%	90.0%	12.0%	0.42	0.48
Basic Coordination Alternative	7,552	27.8%	87.2%	12.8%	0.48	0.56
Enhanced Coordination Alternative	7,897	28.9%	99.5%	0.5%	0.58	0.58
Maximum Operational Flexibility Alternative	8,846	35.5%	91.3%	8.6%	0.59	0.65
Supply Driven Alternative	7,438	27.3%	81.5%	18.5%	0.45	0.55
Representative Preferred Alternative	7,933	29.2%	86.4%	13.6%	0.50	0.58

[1] The total number of HFE eligible timesteps is 27,200 (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

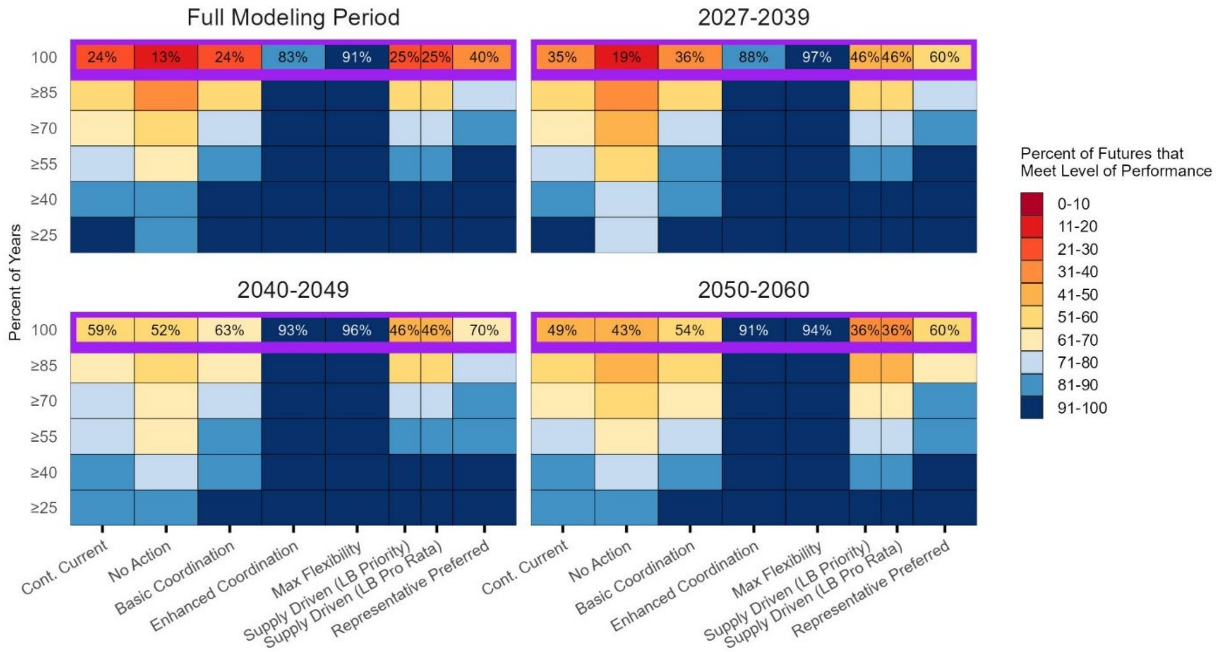


Figure TA 5-3 shows the same information as **Figure TA 5-2** but for an elevation threshold of 3,523 feet, the lowest Lake Powell elevation in the historic record. Once again, the Enhanced Coordination and Maximum Operational Flexibility Alternatives clearly outperform the other alternatives and the CCS Comparative Baseline, but the percentage of futures that meet the preferred minimum performance (26 percent and 21 percent, respectively) is substantially lower than in **Figure TA 5-2**, as an elevation of 3,500 feet is a less stringent threshold than 3,523 feet and therefore easier to achieve. 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**).

Based on the planned length of this decision, it is important to compare robustness in the 2027-2039 modeling period. As in the full modeling period, Enhanced Coordination (29 percent) and Maximum Operational Flexibility (24 percent) are the most robust alternatives. The No Action Alternative is the least robust (3 percent), followed closely by the CCS Comparative Baseline (4 percent) and the Basic Coordination Alternative (6 percent). The Supply Driven (both LB Priority and Pro Rata approaches) Alternative (12 percent) and the Representative Preferred Alternative (14 percent) perform in the middle over the first modeling period.

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

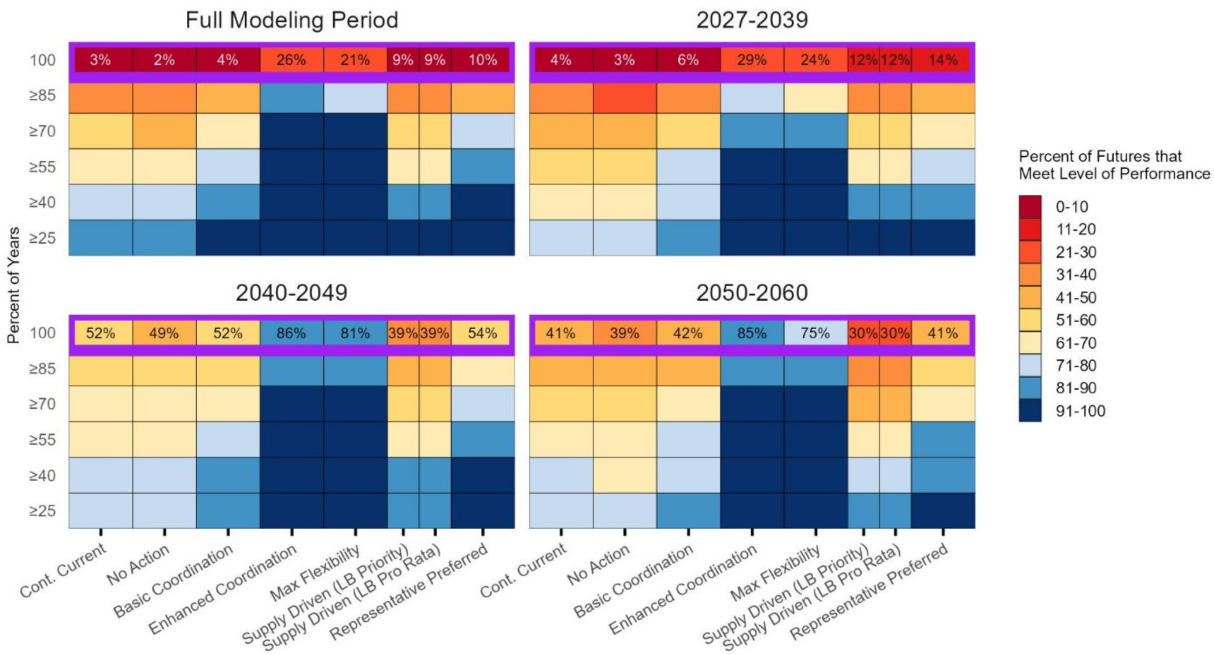
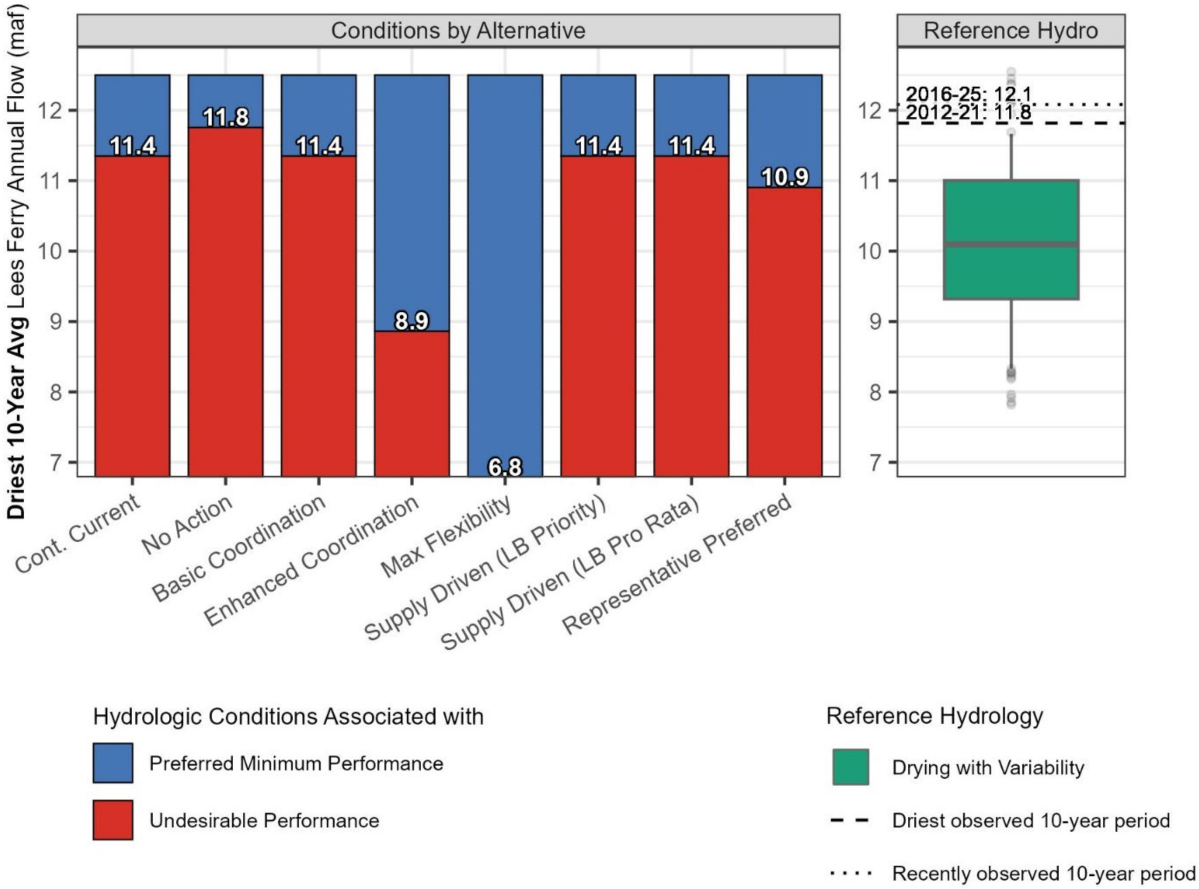


Figure TA 5-4 below shows what flow conditions are likely to cause the elevation of Lake Powell to fall below 3,500 feet in November and April in one or more sediment years. This definition of undesirable performance is based on the highlighted row in **Figure TA 5-2** above, which defined a future as successful when an alternative exceeds 3,500 feet in November or April in 100 percent of years.

For this vulnerability analysis, the driest 10-year average Lees Ferry annual flow was determined to be best for predicting undesirable performance. The vulnerability threshold for each alternative is described and compared to the Drying with Variability ensemble using this streamflow summary statistic. The driest observed 10-year average flow from 2012–2021 (11.8 million acre-feet [maf]) and the average flow from 2016–2025 (12.1 maf) are also provided as dashed and dotted lines, respectively, for comparison (see **Chapter 3, Figure 3-4**, for more information on the selected reference hydrology).

Modeling results for the CCS Comparative Baseline indicate undesirable performance under futures whose driest 10-year average flow is 11.4 maf or lower. Modeling results for the No Action (11.8 percent), Basic Coordination (11.4 percent), and Supply Driven (both LB Priority and LB Pro Rata approaches) (11.4 percent) Alternatives are comparable to the CCS Comparative Baseline, where greater than 75 percent of reference hydrology Drying with Variability traces have 10-year average annual flows drier than these alternatives (see **Appendix F**, Approach to Hydrologic Uncertainty, for more information on the Drying with Variability ensemble). Enhanced Coordination Alternative modeling results indicate undesirable performance when the driest 10-year average flow is 8.9 maf or lower, which occurs in less than 25 percent of the Drying with Variability traces. Modeling results for the Maximum Operational Flexibility Alternative, the best performing alternative in this case, indicate undesirable performance when the driest 10-year average flow is 6.8 maf or lower, which is notably lower than the driest observed 10-year average annual flow of 11.8 maf.

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



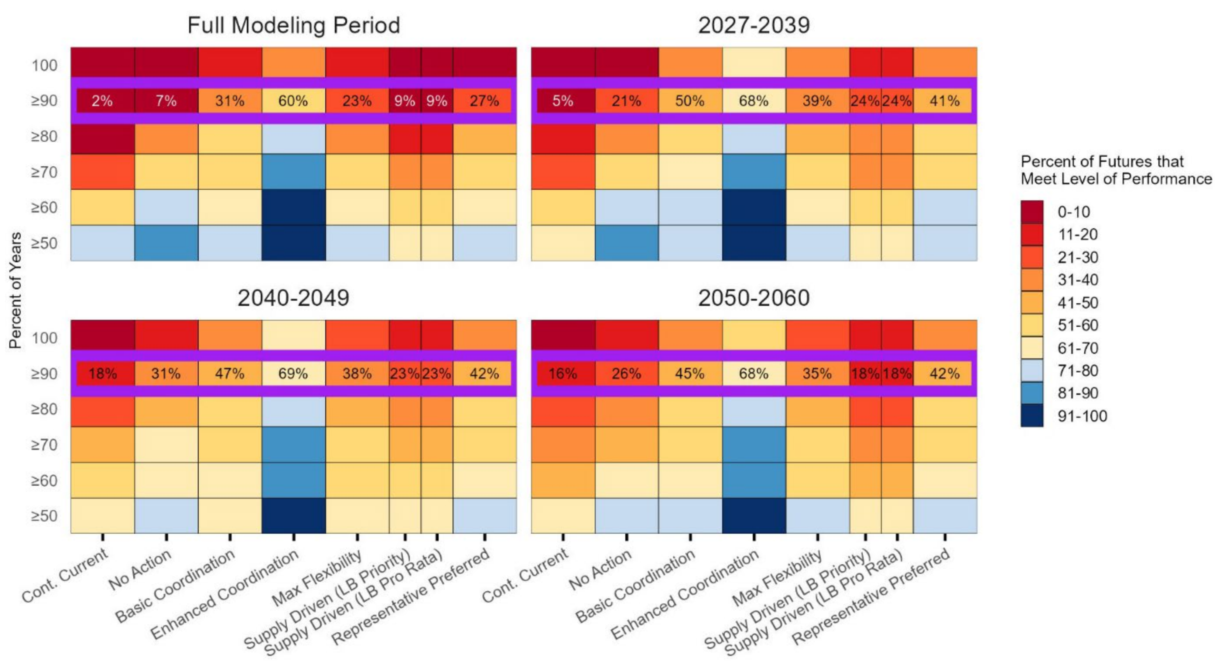
Modeling indicates that the Representative Preferred Alternative would likely be vulnerable to one or more occurrences of Lake Powell elevation falling below 3,500 feet in November and April under a 10-year average Lees Ferry annual flow of 10.9 maf. While these conditions have not yet been observed, absent additional action, this alternative is reasonably likely to be vulnerable in the next 10 years because these conditions occur in about 75 percent of the traces in the Drying with Variability Ensemble, which represents a drier future.

TA 5.2.3 Issue 2: Sand Mass

Sand in the Colorado River must be available to allow for downstream conveyance and sandbar deposition during an HFE release. Sand that accumulates in Marble Canyon but is transported downstream outside HFE events does not result in sandbar formation. Sand available for sandbar building is generally supplied to the Colorado River in the late summer and early fall, the thunderstorm-induced flood season in the Paria and Little Colorado watersheds. While management under the proposed alternatives would not attempt to control the sediment generation in these tributaries, the alternatives would affect the timing and magnitude of Glen Canyon Dam releases and, therefore, the amount of sand transported outside HFE events.

Figure TA 5-5 below depicts the ability of each alternative to maintain a sediment year maximum monthly release from Glen Canyon Dam less than 900 thousand acre-feet (kaf) (approximately 15,000 cfs) in the specified percent of years. While average monthly flows must be lower than about 11,000 cfs to allow sediment accumulation under most initial conditions (bed conditions following a tributary sediment-supply event), monthly flows averaging greater than 15,000 cfs are likely to be erosive regardless of those initial conditions (Salter et al. 2025). Therefore, monthly outflows exceeding 900 kaf are considered erosive for accumulated sand. The preferred minimum performance is shown in the purple highlighted row, which represents the percentage of futures that an alternative maintains a sediment year maximum monthly release from Glen Canyon Dam less than 900 kaf in at least 90 percent of years.

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



Over the full modeling period, the Enhanced Coordination Alternative is the most robust, meeting the preferred minimum performance in 60 percent of futures. The next best-performing alternatives are Basic Coordination at 31 percent, Representative Preferred Alternative at 27 percent, and Maximum Operational Flexibility at 23 percent. The No Action Alternative is the least robust, with only 7 percent of futures meeting the preferred minimum performance. Under the CCS Comparative Baseline, as well as No Action and Supply Driven (both LB Priority and LB Pro Rata approaches) Alternatives, less than 10 percent of simulated futures satisfy the preferred minimum performance.

Fewer futures meet the preferred minimum performance over the full modeling period than they do in any one of the subperiods, a reflection of the increasing difficulty of sustaining this performance level over a longer period and evidence of the interdecadal variability inherent in the ensemble of projected conditions.

Based on the planned length of this decision, it is important to compare robustness in the 2027-2039 modeling period. Enhanced Coordination (68 percent) and Basic Coordination (50 percent) are the most robust alternatives. The CCS Comparative Baseline (5 percent) is the least robust, followed by the No Action (21 percent) and Supply Driven (both LB Priority and Pro Rata approaches) (24 percent) Alternatives. The Maximum Operational Flexibility and the Representative Preferred Alternatives perform in the middle, meeting the preferred minimum performance in 39 percent and 41 percent of futures, respectively, over the 2027-2039 modeling period.

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 kaf per month, management flexibility will be allowed for the maximum preservation of sand mass.

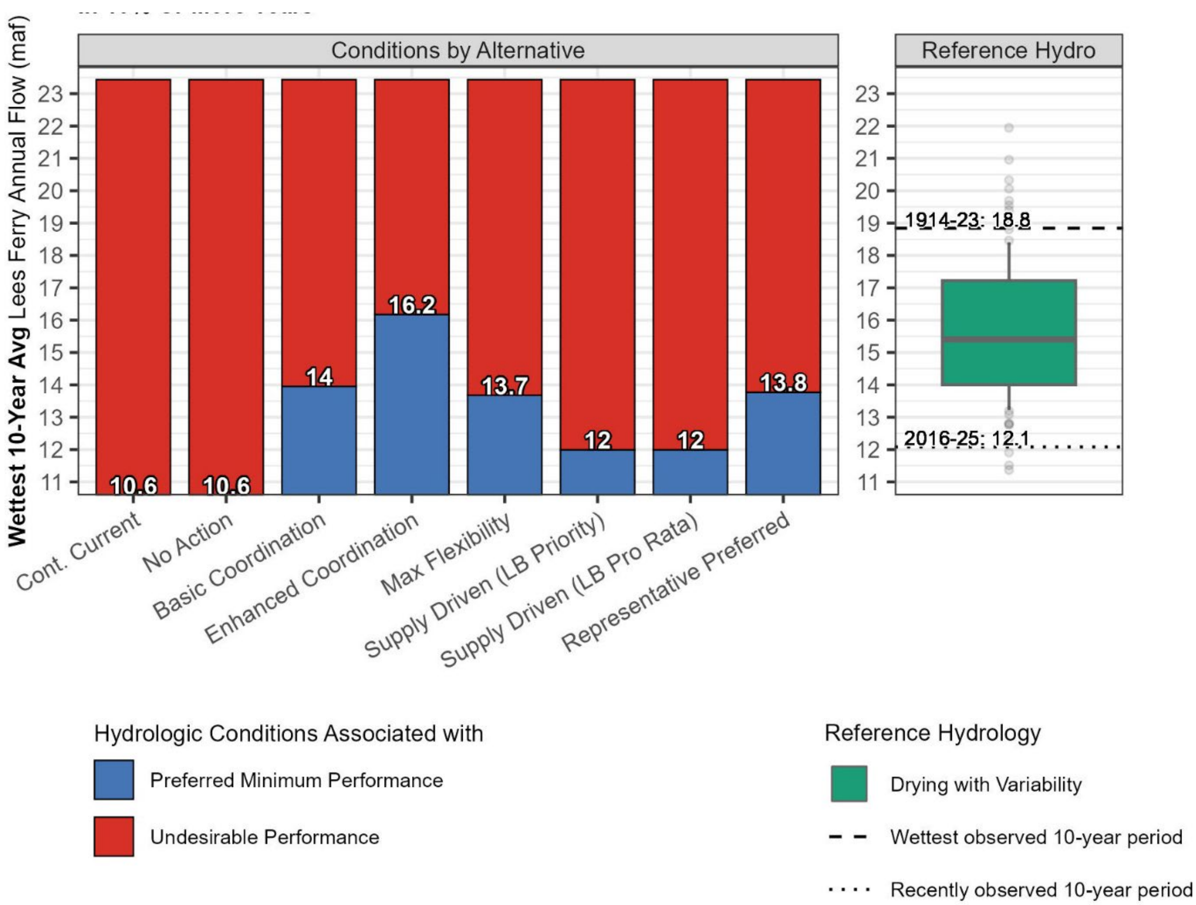
Figure TA 5-6 below shows what flow conditions are likely to cause the Glen Canyon Dam maximum monthly outflow to exceed 900 kaf in more than 10 percent of years. This definition of undesirable performance is based on the highlighted row in **Figure TA 5-5** above, which defined a future as successful when an alternative maintains a sediment year maximum monthly release from Glen Canyon Dam less than 900 kaf in at least 90 percent of years

For this vulnerability analysis, the wettest 10-year average Lees Ferry annual flow was determined to be skillful at predicting undesirable performance. The vulnerability threshold for each alternative is described and compared to the Drying with Variability ensemble using this streamflow summary statistic. The wettest observed 10-year average flow from 1914–1923 (18.8 maf) and the average flow from 2016–2025 (12.1 maf) are also provided as dashed and dotted lines, respectively, for comparison.

Modeling results for the CCS Comparative Baseline and the No Action Alternative indicate undesirable performance under futures whose wettest 10-year average annual flow is 10.6 maf or higher, which is below the most recently observed 10-year average annual flow of 12.1 maf. Performance is almost as poor for the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches), where undesirable performance occurs under futures whose wettest 10-year average flow is 12.0 maf or higher. Under Basic Coordination and Maximum Operational Flexibility

Alternatives, undesirable performance occurs when the wettest 10-year average flow is 14.0 and 13.7 maf or higher, respectively, which occurs in about 75 percent of the projected hydrology traces. Least vulnerable to projected conditions is the Enhanced Coordination Alternative, under which undesirable performance occurs when the wettest 10-year average flow is 16.2 maf or higher, occurring in less than 50 percent of the projected hydrology traces.

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

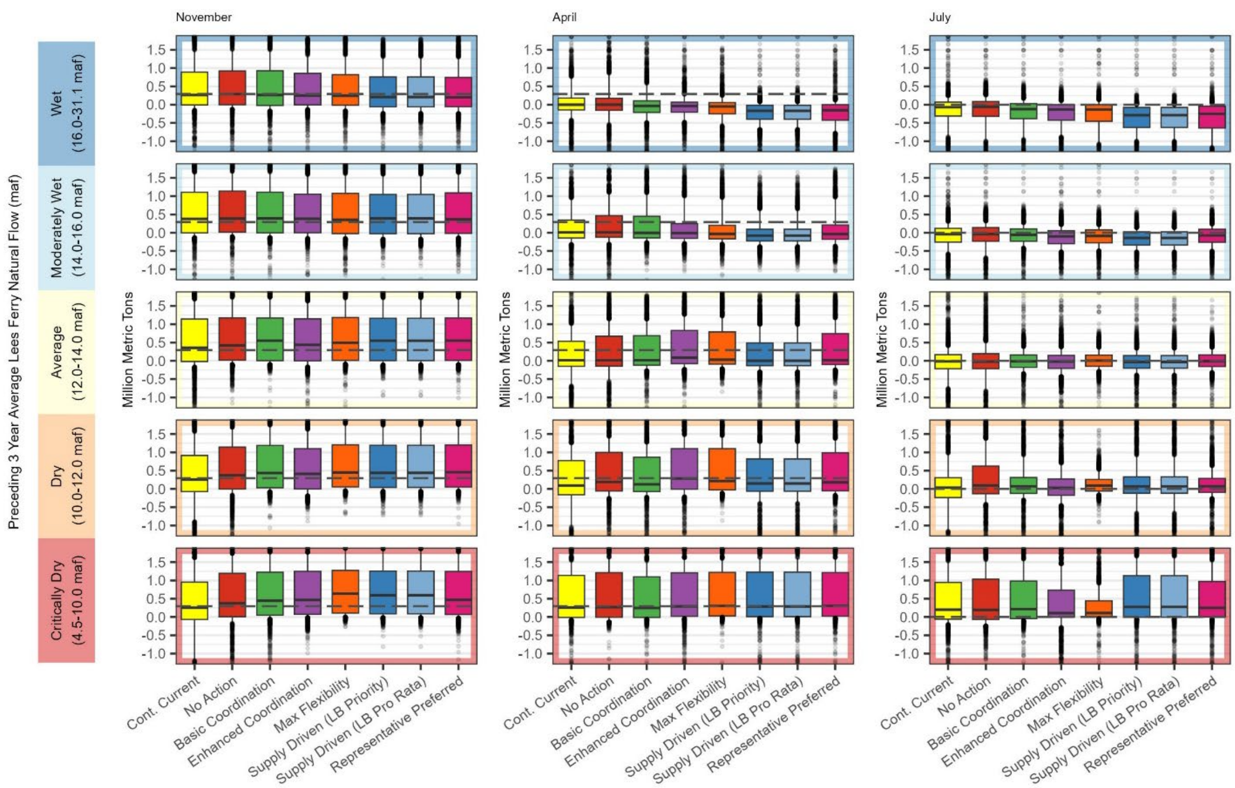


The Representative Preferred Alternative is likely to be vulnerable if the wettest 10-year average Lees Ferry annual flow is 13.8 maf or higher. Compared to the historical periods shown in the Reference Hydrology panel, this flow has occurred before; though, this alternative may or may not be vulnerable in the next 10 years because different aspects of the panel conflict. Considering the Drying with Variability ensemble, about 75 percent of traces are greater than 13.8 maf, suggesting this alternative is reasonably likely to be vulnerable. However, the recently observed 10-year period (of 12.1 maf) is below 13.8 maf, suggesting that this alternative is unlikely to be vulnerable if the next 10 years are similar to or drier than the most recent 10 years.

All of the alternatives are vulnerable to historical conditions, of which the wettest 10-year period averaged 18.8 maf annually. Four of the alternatives (the CCS Comparative Baseline, No Action, and Supply Driven [both LB Priority and LB Pro Rata approaches] Alternatives) would have been vulnerable during the most recently observed 10-year period (2016-2025), which had an average flow of 12.1 maf.

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]). Negative values indicate sand depletion. The distributions are further categorized according to five hydrologic conditions based on the average natural flow at Lees Ferry over the preceding 3-year period.

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



Interpretation of **Figure TA 5-7** depends on the three periods of interest. From July to November, it is preferable for sand accumulation to exceed 294,000 metric tons (indicated by a dashed line in the November column). Since 294,000 metric tons is the average transport capacity for an HFE event of 60 hours, the duration at which successful beach building occurs, sand accumulation exceeding this threshold allows for a fall HFE event (provided enough water is available in Lake Powell). If that is not possible, sand accumulation from July to April exceeding 294,000 metric tons (indicated by a dashed line in the April column) allows for a spring HFE event. In either case, it is preferable for annual sand accumulation from July to July to be near zero (indicated by a dashed line in the July column), which suggests sand accumulated during the prior sediment year was subsequently depleted via an HFE event.

For all five hydrologic conditions, most sand accumulation in Marble Canyon occurs from July to November, the summer-fall thunderstorm season during which the Paria and Little Colorado Rivers are most active. 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.

In the Moderately Wet and Wet Flow Categories, 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. From November to April, larger than normal releases outside of HFE events are likely to contribute to sediment depletion, resulting in a median change in sand mass between July and April of close to zero. While very little change in sand mass occurs from April to July, indicating spring HFEs are uncommon during these conditions, slightly more depletion occurs on an annual basis under the Wet Flow Category.

In the Average and Dry Flow Categories, sand is also depleted 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 from July to April, allowing for spring HFE events. The gradual decrease in sand mass continues from April to July, so that on an annual basis (July 1 to July 1), there is little net change in sand mass, similar to the wettest two categories.

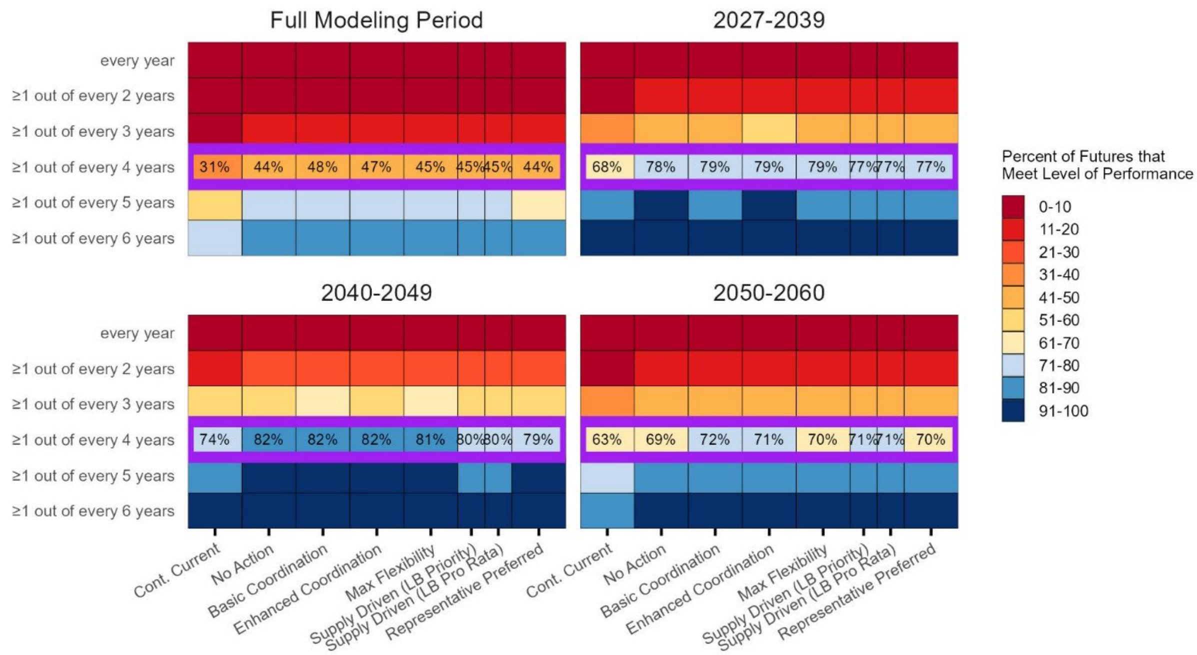
All six alternatives perform comparably across the four flow categories above. Only in the Critically Dry Flow Category does meaningful differentiation exist among performance. In general, there is little change in sand mass from both November to April and April to July, indicating HFE events are infrequent. However, on an annual basis, a smaller level of accumulation occurs for the Maximum Operational Flexibility and (somewhat) Enhanced Coordination Alternatives, suggesting they are slightly more conducive to HFE events during these conditions.

Figure TA 5-8 shows how often Marble Canyon sand mass exceeds 294,000 metric tons, the average transport capacity for a 60-hour HFE, in November or April. A 60-hour duration is required for successful beach building. The highlighted row shows the percentage of futures that meet this condition at least once every 4 years, the preferred minimum performance. As stated in the Methodology (see **TA 5.2.1**, Methodology), each future was randomly assigned a trace of Paria River sediment input (however, each future/sediment trace combination was kept the same across the alternatives).

Aside from the CCS Comparative Baseline, the other alternatives are similarly robust. The percentage of futures in which the November or April sand mass exceeds 294,000 metric tons at least once every 4 years in the other alternatives, ranges from 44 percent to 48 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 4 years. As mentioned earlier for other figures, fewer futures meet the preferred minimum performance over the full modeling period than in any one of the subperiods, a reflection of the increasing difficulty of sustaining this performance level over a longer period and evidence of the interdecadal variability inherent in the ensemble of projected conditions.

Based on the planned length of this decision, it is important to note that, similar to the other action alternatives, the Representative Preferred Alternative meets the preferred minimum performance level in 77 percent of futures in the 2027-2039 modeling period.

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

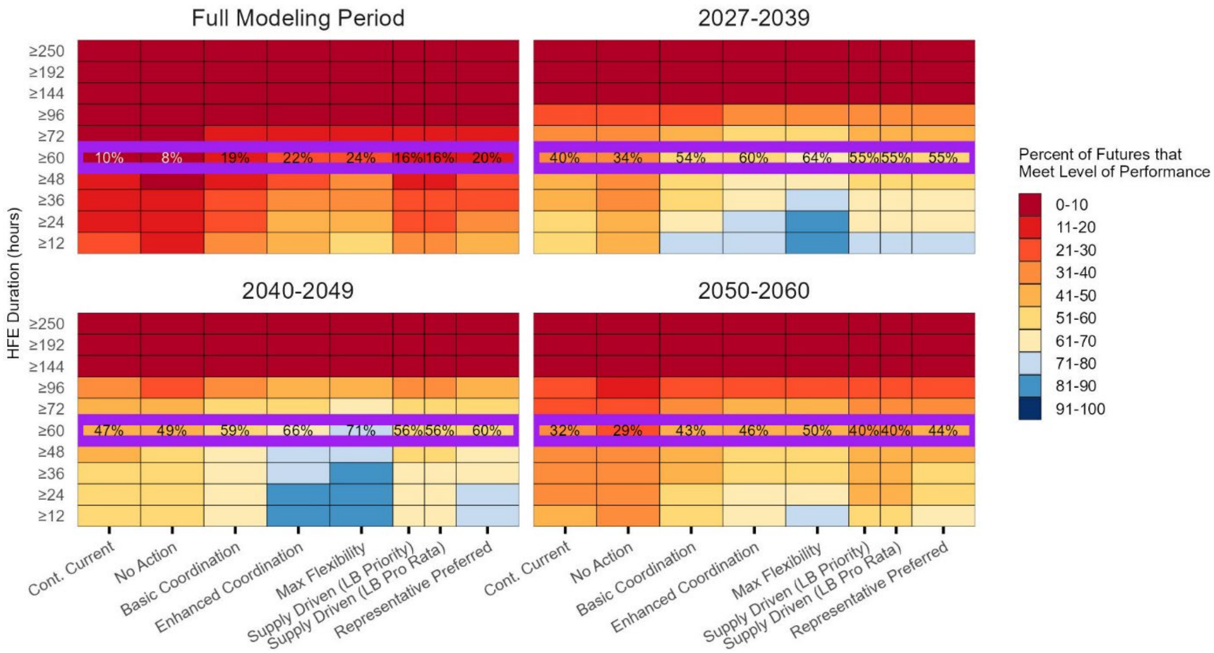


TA 5.2.4 Issue 3: HFE Frequency and Duration

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 have been between 60 and 96 hours.

Figure TA 5-9 shows the percentage of futures in which the annual HFE duration equals the number of hours specified in each row at least once every 4 years. Futures are considered preferable at a duration of 60 hours, the minimum duration associated with significant sandbar deposition. The highlighted row provides the percentage of futures that meet this criterion.

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 4 years



For the full modeling period, none of the alternatives satisfy the preferred minimum performance in more than 24 percent of futures. Fewer futures meet the preferred minimum performance over the full modeling period than in any one of the subperiods, a reflection of the increasing difficulty of sustaining this performance level over a longer period and evidence of the interdecadal variability inherent in the ensemble of projected conditions. For all periods, the action alternatives are similarly robust and perform better than the CCS Comparative Baseline and No Action Alternative, with the Maximum Operational Flexibility Alternative performing slightly better than the others. It is important to note the modeling does not imply an expected outcome, just that HFEs remain possible. HFE triggers and final HFE implementation would be a result of the LTEMP process.

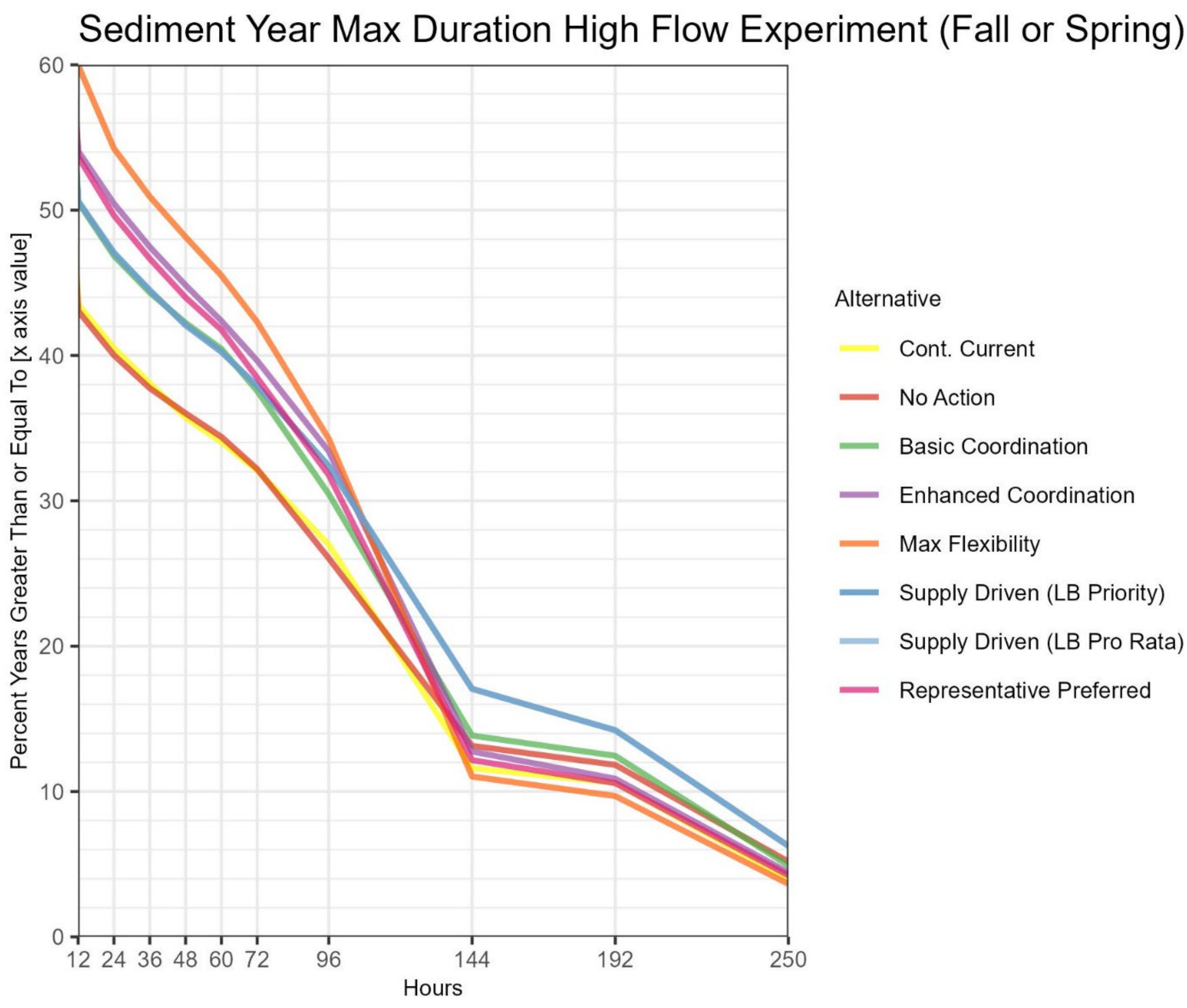
Based on the planned length of this decision, it is important to compare robustness in the 2027-2039 modeling period. The Representative Preferred Alternative meets the preferred minimum performance level in 55 percent of future which is the same as the Supply Driven Alternative (both LB Priority and Pro Rata approaches) and similar to the Basic Coordination Alternative (54 percent). The Maximum Operational Flexibility (64 percent) and Enhanced Coordination (60 percent) Alternatives are more robust. The No Action Alternative (34 percent) and CCS Comparative Baseline (40 percent) meet the preferred minimum performance least often in the first decade.

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. An HFE of 60 hours or longer occurring at least once every 4 years is the preferred minimum performance. While

Figure TA 5-10 does not directly address this indicator, it suggests the likelihood with which it is met.

For HFE releases lasting 12 to 96 hours, the Maximum Operational Flexibility, Enhanced Coordination, and Representative Preferred Alternatives perform the best, with 46, 43, and 42 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) performs 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.

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



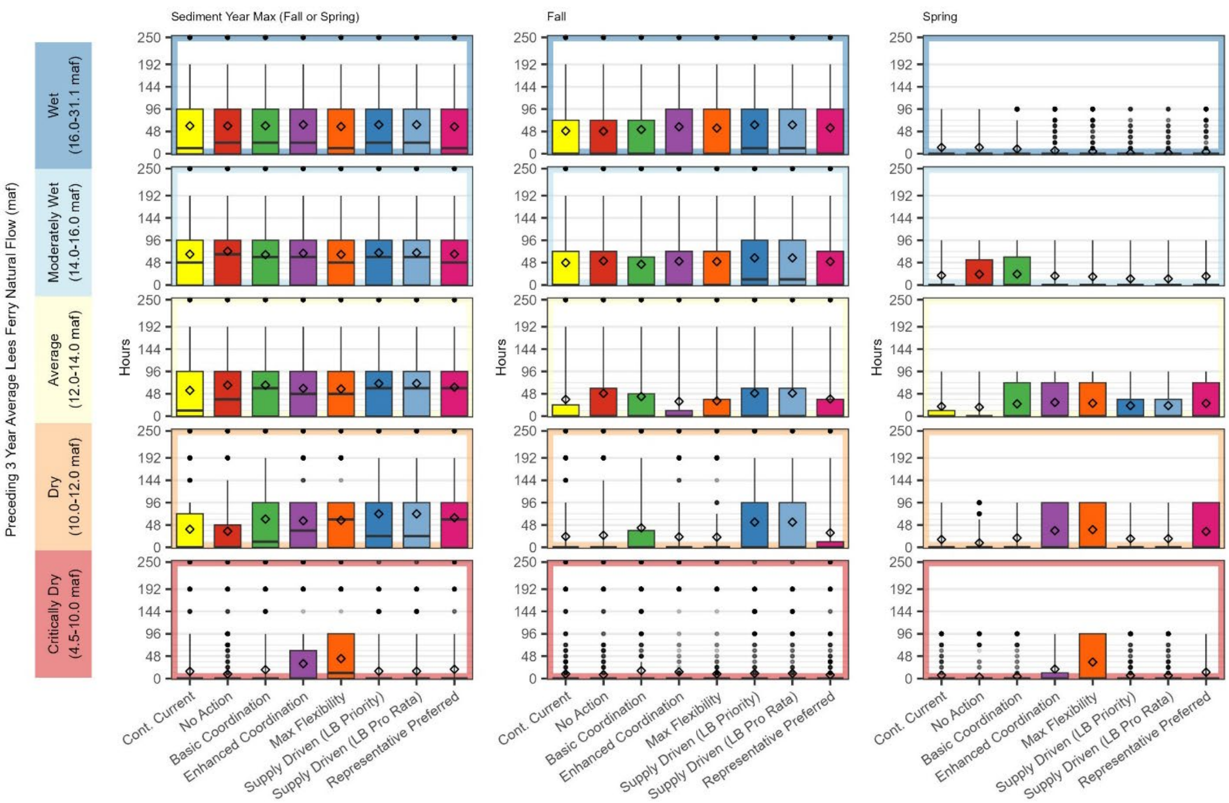
The worst performance generally occurs under the CCS Comparative Baseline and the No Action Alternative. Their performance is comparable for HFE durations below 144 hours. For HFE durations above 144 hours, the No Action Alternative performs slightly better than the CCS

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 5-10** indicates that, across all alternatives, 60-hour HFEs would occur in 36 to 46 percent of years simulated, **Figure TA 5-9** indicates 60-hour HFEs every 4 years would occur in only 10 to 25 percent of futures. This suggests 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 natural flow at Lees Ferry over the preceding 3-year period. As stated above, the preferred minimum performance is an HFE lasting 60 hours or longer at least once every 4 years. The Methodology (see **TA 5.2.1**) indicates that for an HFE to be scheduled, enough sand must be available in Marble Canyon, and enough water must be available in Lake Powell. If enough sand and water are available, longer HFE's could be scheduled. 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



The performance of alternatives in **Figure TA 5-11** varies by flow category. For the two wettest categories, the distribution of annual HFE durations over the full sediment year is comparable across all alternatives, with the majority of HFEs occurring in the fall. For the Average Flow

Category, HFE durations over the full sediment year are again comparable, but the timing of HFEs for the Basic Coordination, Enhanced Coordination, Maximum Operational Flexibility, and Representative Preferred Alternatives begins to shift from fall to spring. This trend continues for the two driest flow categories, with only the Enhanced Coordination and Maximum Operational Flexibility Alternatives resulting in HFEs of any significant duration in the Critically Dry Flow Category, typically occurring in the spring.

Notably, for all alternatives in all flow categories, the 75th percentile of HFE durations for the full sediment year is typically higher than it is in either fall or spring. This is due to the larger sample size of fall HFEs, whose high outliers serve to increase the 75th percentile for the full sediment year.

TA 5.2.5 Issue 4: Sandbar Volume

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, represents the volume of "usable" sand in the canyon. In general, larger sandbar volumes are preferable over smaller sandbar volumes.

Figure TA 5-12 shows distributions of "usable" sandbar volume, further categorized according to five hydrologic conditions based on the average natural flow at Lees Ferry over the preceding 3-year period. As the preferred minimum performance, sandbar volumes should exceed their volume at the start of the simulation period for at least 60 percent of modeled years. The average sandbar volume for the 25 sandbar monitoring sites at the start of the simulation period is 1169.512 cubic meters, indicated by a dashed horizontal line.

For all but the Wet Flow Category, all alternatives show sandbar growth in greater than 60 percent of years, with nearly all alternatives showing sandbar growth in greater than 75 percent of years. For the Wet Flow Category, the Basic Coordination, Supply Driven (both LB Priority and LB Pro Rata approaches), and Representative Preferred Alternatives show sandbar growth in greater than 60 percent of years, and 25th percentile sandbar volumes for all alternatives are lower than the initial condition (1169.512 cubic meters on average for the 25 sandbar monitoring sites). In general, sandbar growth increases as hydrologic conditions become drier. Differences in performance among the alternatives also increase as hydrologic conditions become drier, with the Enhanced Coordination and Maximum Operational Flexibility Alternatives clearly performing the best for the Critically Dry Flow Category.

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). Here again, the average sandbar volume for the 25 sandbar monitoring sites at the start of the full simulation period (2027) is 1169.512 cubic meters; initial sandbar volumes for subperiods depend on the hydrology trace. It is important to note that **Figure TA 5-13** does not show the percentage of years with year-over-year sandbar growth; if large increases in sandbar volume occur at the start of a period, 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.

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

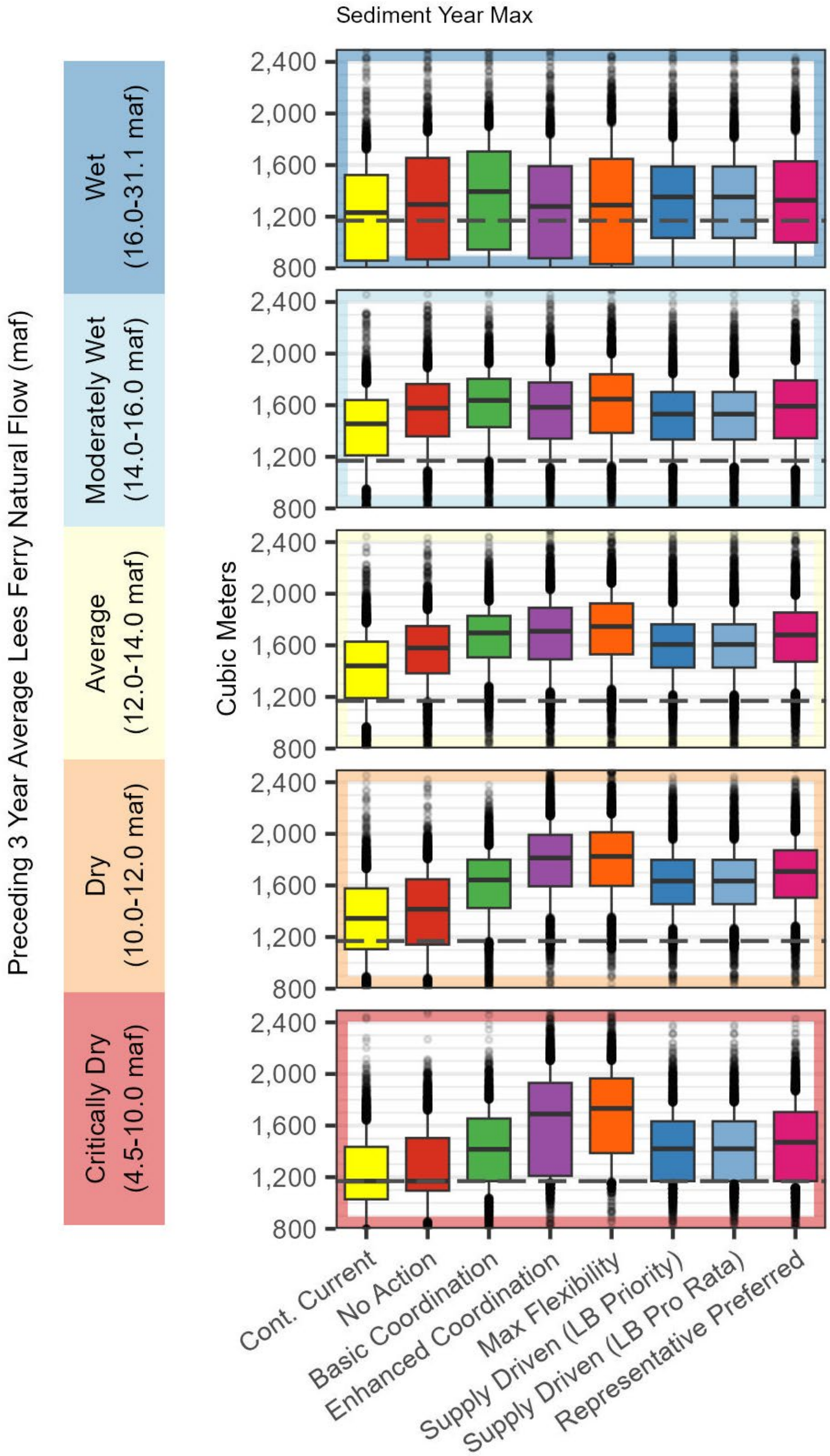
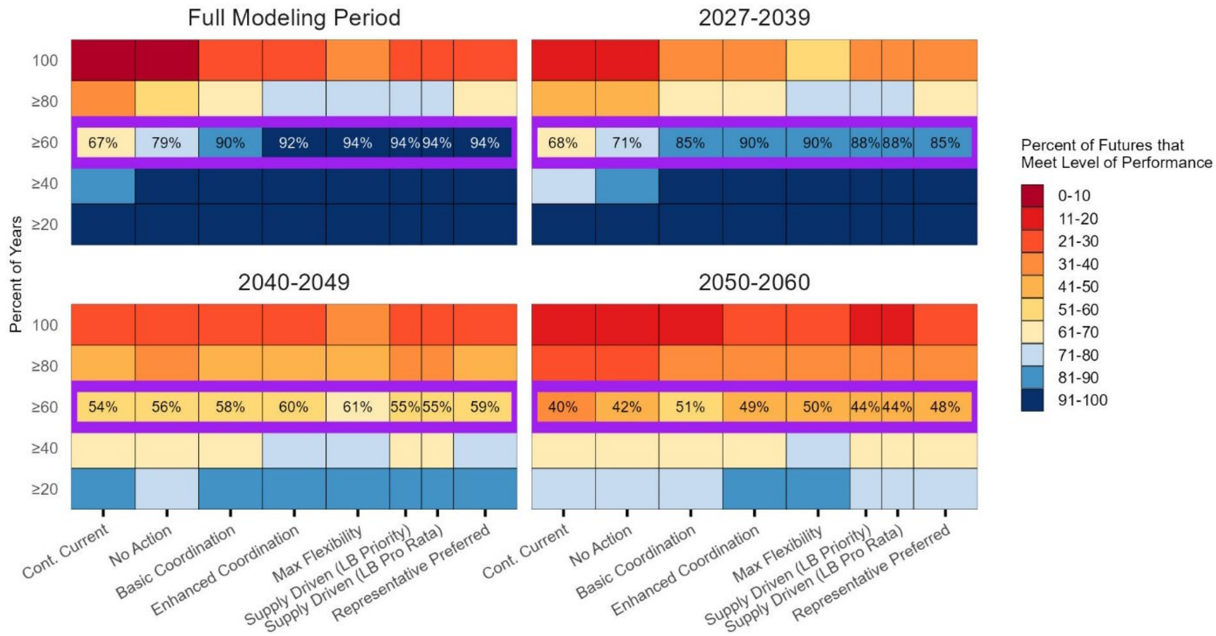


Figure TA 5-13
Long-Term Sandbar Growth: Robustness.
Percent of futures in which the weighted average sandbar volume of Grand Canyon and Marble canyon has increased relative to the start of each period in the percent of years specified in each row



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.

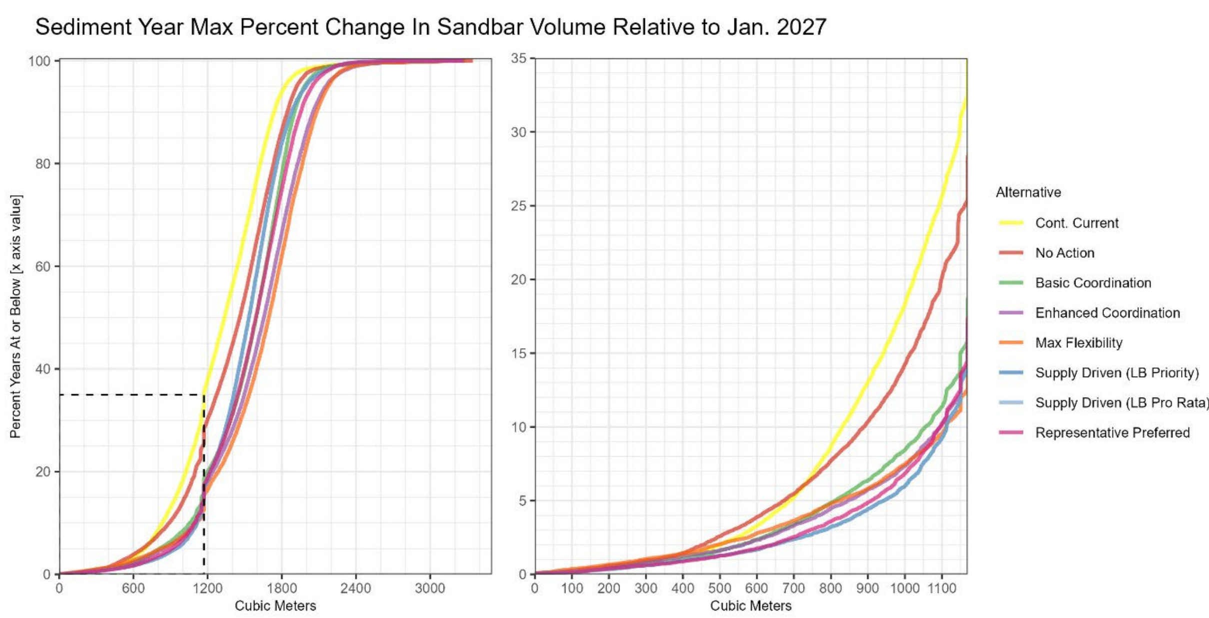
Over the full modeling period, the Maximum Operational Flexibility, Enhanced Coordination, Supply Driven (both Priority and Pro Rata approaches), and Representative Preferred Alternatives are truly robust, meeting the minimum preferred performance level in over 90 percent of years. Though slightly less, the Basic Coordination Alternative is similarly robust, meeting the minimum preferred performance level in 90 percent of years. Performance level is lowest for the No Action Alternative and CCS Comparative Baseline, with the latter being the least robust. Most of the increase occurs in the first 13-year period, after which sandbar growth slows, possibly because of the larger sandbar volumes, and fewer opportunities for deposition, at the start of the other subperiods.

In general, a relatively high percentage of futures (at least 90 percent for all five action alternatives) meet the preferred minimum performance of more than 60 percent of years with net sandbar growth. This contrasts with figures such as **Figure TA 5-9**, where no more than 24 percent of futures meet the preferred minimum performance of 60-hour HFEs at least once every 4 years. The discrepancy is due to the definition of sandbar growth with respect to the *beginning* of a period, which allows for the possibility that years without an HFE might still meet this preferred minimum performance. In addition, each future is based on a single simulation and consequently subdivided into the three modeling subperiods. Consequently, the initial conditions for the 2040–2049 and 2050–2060 modeling periods depend on the simulation and differ for each future. The significant increase in sandbar volume during the 2027–2039 modeling period could be partially attributed to the modeling assumption that HFEs are implemented as often as possible (see **TA 5.2.1**, Methodology).

Based on the planned length of this decision, it is important to note that, similar to the other action alternatives, the Representative Preferred Alternative meets the preferred minimum performance level in 85 percent of futures in the 2027-2039 modeling period. The CCS Comparative Baseline (68 percent) and No Action Alternative (71 percent) are less robust over the first modeling period.

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. The average sandbar volume for the 25 sandbar monitoring sites at the start of the full modeling period is 1169.512 cubic meters (see **TA 5.2.1**, Methodology).

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



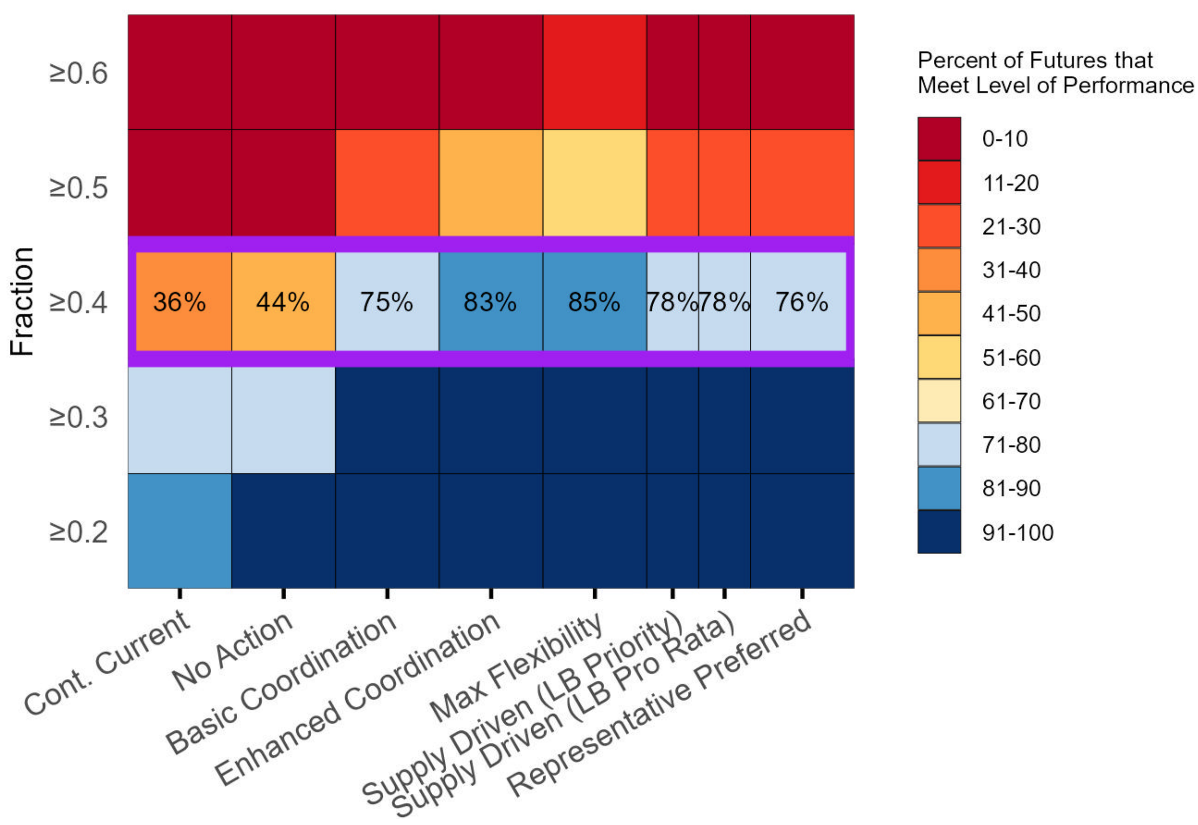
With respect to the initial condition, the five action alternatives perform comparably, all resulting in average sandbar volumes smaller than 1169.512 cubic meters 13 to 15 percent of the time for the 25 sandbar monitoring locations. For very small sandbar volumes (less than 1000 cubic meters), the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) performs slightly better than the others. Performance under No Action lags behind, 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, 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 that is available for sandbar formation (Hazel et al. 2022; Salter et al. 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) exceeds 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



Under the best performing alternatives, the Maximum Operational Flexibility and Enhanced Coordination, 85 and 83 percent of simulated futures, respectively, meet the minimum preferred performance level, i.e., at least 40 percent of sand mass is transported by sandbar-forming flow rates in 85 and 83 percent of simulated futures, respectively. The next best performance occurs under the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches), for which 78 percent of futures meet the preferred minimum performance, followed by the similarly robust Representative Preferred and Basic Coordination Alternatives, for which 76 and 75 percent of futures meet the preferred minimum performance, respectively. 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

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