Technical Appendix 6

Water Quality

This page intentionally left blank.

Contents

Tables

Figures

Acronyms and Abbreviations

Acronym or Abbreviation	Full Phrase
°C	degrees Celsius
°F	degrees Fahrenheit
CCS	Continued Current Strategies
CRSS	Colorado River Simulation System
DMDU	Decision Making Under Deep Uncertainty
LB	Lower Basin
maf	million acre-feet
Mexico	United Mexican States
mg/L	milligrams per liter
PFAS	per- and polyfluoroalkyl substances
TDS	total dissolved solids
WY	water year

This page intentionally left blank.

TA 6. Water Quality

TA 6.1 Affected Environment

This section describes selected water quality constituents that could be affected by the alternatives. These water quality constituents of concern are:

- Salinity
- Temperature
- Harmful algal blooms and nutrients
- Dissolved oxygen
- Metals
- Perchlorate
- Per- and polyfluoroalkyl substances (PFAS)

Other water quality issues were considered but are not discussed here, as they were unlikely to be affected by the alternatives or lacked sufficient data for assessment.

TA 6.1.1 Salinity

Historically, elevated salinity levels have been a concern for the Basin, as higher salinity concentrations cause economic damage across agricultural, municipal, and industrial sectors in the U.S., and negatively impact municipal and agricultural users in the United Mexican States (Mexico) (USGS 2021). To address these issues, in 1974 Congress enacted the Colorado River Basin Salinity Control Act, which directed the Secretary of the Interior to proceed with a program to enhance and protect the quality of water available in the Colorado River for use in the United States and Mexico. In 1975, the Environmental Protection Agency approved water quality standards developed by the seven Colorado River Basin States in response to the Federal Water Pollution Control Act of 1972. The standards included numeric criteria for three stations on the mainstem of the lower Colorado River (below Hoover Dam, below Parker Dam, and at Imperial Dam) and a Plan of Implementation to control salinity increases.

The Colorado River Basin Salinity Control Forum continues to review and make salinity criteria recommendations for the Colorado River every 3 years (Colorado River Basin Salinity Control Forum 2023). **Table TA 6-1** shows the current salinity criteria for the Colorado River.

Table TA 6-1
Salinity Criteria for the Colorado River

Station	Flow-weighted average annual salinity (milligrams per liter [mg/L])
Below Hoover Dam	723
Below Parker Dam	747
At Imperial Dam	879

Source: Colorado River Basin Salinity Control Forum 2023

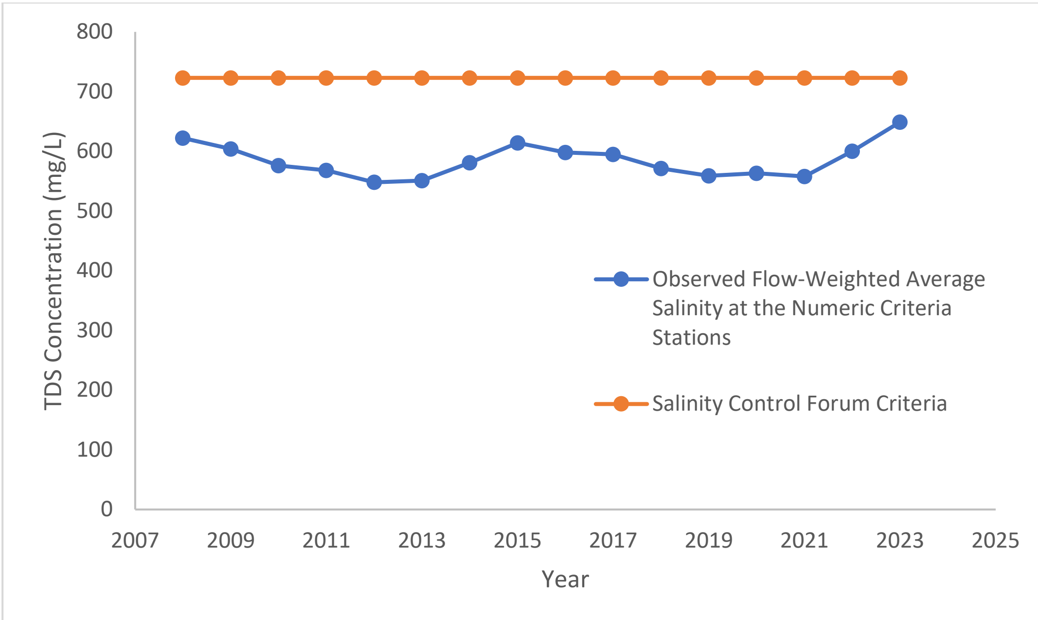
Salinity control is accomplished through multiple programs. The U.S. Department of Agriculture's Environmental Quality Incentives Program provides cost-share assistance to landowners who install salinity control measures (Reclamation 2022). Additionally, federal agencies, including the Bureau of Reclamation (Reclamation), the Bureau of Land Management, and the United States Department of Agriculture, pursue improvement on federal lands to reduce salinity loading to the Colorado River. Despite these efforts, salinity trends have plateaued since 2000, after decreasing throughout the twentieth century (Rumsey et al. 2021). Total dissolved solids[1] loads increase during wet periods and decrease during dry periods, so increased regional aridification may be contributing to decreasing stream salinity through quicker surface runoff and lagged groundwater storage processes (Miller et al. 2024; Brooks et al. 2025). Conversely, increased aridification may increase concentrations, as 89 percent of total dissolved solids loads is derived from the baseflow fraction of streamflow, and declines in surface runoff are expected to outpace changes in baseflow contributions to streamflow (Rumsey et al. 2017).

Since the construction of Glen Canyon Dam, annual salinity concentration downstream of Glen Canyon Dam varies between 400 and 600 mg/L (Richards 2025). Within Lake Powell, reservoir stratification results in different salinity concentrations at different depths. Releases from lower elevations in Lake Powell through the river outlet works are generally more saline compared with releases from higher elevations through the penstocks of Glen Canyon Dam (Reclamation 2016). See **TA 6.1.2** for a more complete discussion of reservoir stratification.

In a review of sampling efforts from 2007–2023, Reclamation has not exceeded the salinity criteria for the Colorado River, which are described in **Table TA 6-1**. See **Figure TA 6-1**, **Figure TA 6-2**, and **Figure TA 6-3** for more information and historical salinity concentrations in the Lower Colorado River Basin. Salinity concentrations are based on total dissolved solids concentrations and are used interchangeably in this discussion.

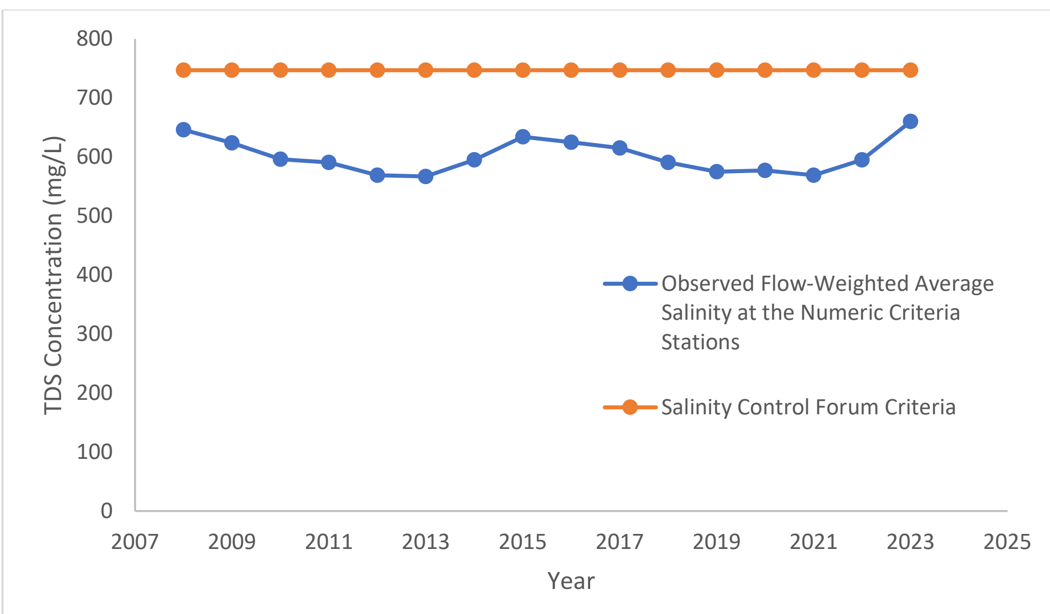
[1] Total dissolved solids are the combined content of all substances in a liquid volume and is related to salinity, which is the total concentration of all dissolved salts in water. The sum of constituents is defined to include calcium, magnesium, sodium, chloride, sulfate, a measure of the carbonate equivalent of alkalinity and, if measured, silica and potassium. The two terms are often used interchangeably in Colorado River salinity discussions.

Figure TA 6-1
Colorado River Salinity Concentrations and Flows Downstream of Hoover Dam
2008–2023



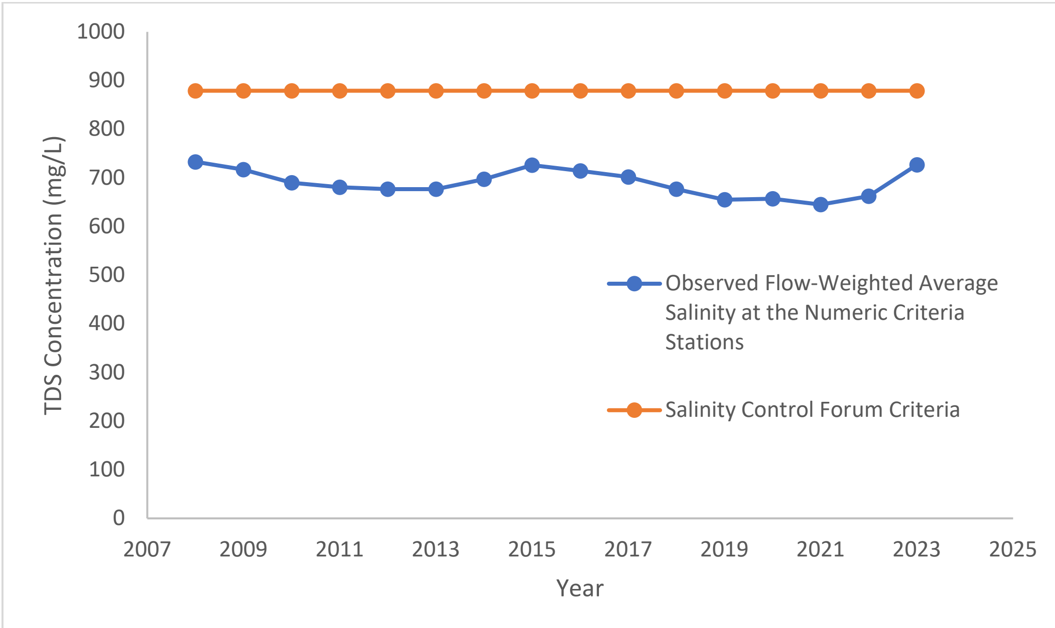
Source: Richards 2025

Figure TA 6-2
Colorado River Salinity Concentrations and Flows Downstream of Parker Dam
2008–2023



Source: Richards 2025

Figure TA 6-3
Colorado River Salinity Concentrations and Flows at Imperial Dam 2008–2023



Source: Richards 2025

TA 6.1.2 Temperature

Lake Powell is a monomictic[2] reservoir with strong thermal stratification through much of the spring, summer, and early fall; this means Lake Powell is arranged into layers with distinct temperatures and chemical characteristics. Generally, Lake Powell's epilimnion, or uppermost layer, ranges from 25 to 30 degrees Celsius (°C; 77 to 86 degrees Fahrenheit [°F]) in the summer, dropping to 6 to 10 °C (42.8 to 50 °F) in the winter (Deemer et al. 2023). Lake Powell's hypolimnion, or deeper layer, ranges from 6 to 9 °C (42.8 to 48.2 °F) year round. In the winter, the thermal stratification breaks down, and Lake Powell experiences turnover, where the different layers mix to create relatively uniform conditions throughout the water column (Reclamation 2016). Historically, complete mixing of the water column was rare; however, homogenous conditions have been observed more recently with lower reservoir elevations.

Since the early 2000s, lower water levels in Lake Powell have led to warm summer temperatures in the Colorado River below Glen Canyon Dam (Reclamation 2016). Temperatures in the Colorado River in the Grand Canyon are highly variable over space and time and are primarily controlled by the discharge and temperature released from Glen Canyon Dam and solar radiation dynamics along the river corridor (Mihalevich et al. 2020). As water moves farther away from Glen Canyon Dam, the influence of release volume and temperature on water temperature becomes less, and local meteorological conditions become more influential. During summer periods, increases in water temperatures downstream of Glen Canyon Dam are attributed to solar radiation and air temperatures (Dibble et al. 2021). The water in the Colorado River generally warms 1 °C (1.8 °F) for every 30 miles traveled downstream during warmer months of the year under specific discharge and

[2] Monomictic water bodies are those mix completely during one mixing period each year.

meteorological conditions. Some variation in lateral warming also occurs, with warmer temperatures along the shoreline and cooler water in the deep, fast-moving areas (Reclamation 2016).

Lake Mead is also monomitic. Lake Mead inflow temperatures are a function of Glen Canyon Dam discharges and downstream weather conditions (Reclamation 2016). Lake Mead's hypolimnion is around 12 °C (53.6 °F) year-round, and its epilimnion ranges from about 14 to 29 °C (57.2 to 84.2 °F) in the spring, summer, and early fall, dropping to about 13 to 15 °C (55.4 to 59 °F) in the winter (SNWA 2023). During the winter months, Lake Mead experiences turnover in about 50 percent of years. With lower reservoir elevations and increased air temperatures, water temperatures have been increasing, leading to warmer releases from Lake Mead. Further declines in reservoir elevation, coupled with rising air temperatures, may continue to lead to warmer releases from Lake Mead, though this depends on whether the lower Hoover Dam outlet is used (Hannoun et al. 2022).

TA 6.1.3 Harmful Algal Blooms and Nutrients

Nutrients, such as nitrogen and phosphorus, are essential for plant and animal growth and nourishment, but the overabundance of certain nutrients in water can harm human health, affect ecosystems, and impact recreational opportunities (USGS 2019; NPS 2025). Excess nutrients can cause eutrophication, where the accumulation of nutrients in a body of water results in the increased growth of microorganisms, such as algae. Algae can rapidly increase, leading to algal blooms, characterized by unsightly scum on the water surface, and producing toxins that pose serious health risks to humans and animals (NPS 2025). Consumption of dead algae by bacteria consumes dissolved oxygen and may deplete the oxygen in the water column, leading to fish kills (USGS 2019). For more details on the impacts of dissolved oxygen levels in the water column, see the ***Dissolved Oxygen*** section.

The most severe algal blooms are caused by cyanobacteria and have the potential for production of toxins that can threaten drinking water quality and harm human health (USGS 2019). Certain toxins, such as Microcystin-LR cylindrospermopsin, are associated with symptoms such as abdominal pain, headache, and vomiting, while the Anatoxin-a group toxin can lead to symptoms such as tingling, burning, numbness, drowsiness, and respiratory paralysis (EPA 2014). Algal blooms have led to water advisories at recreational sites within the planning area, such as the Glen Canyon National Recreation Area, when the National Park Service detected cyanotoxins. The National Park Service recommended that boaters use caution and avoid unnecessary exposure to the reservoir for recreational activities such as fishing and boating (NPS 2025). See **TA 14.1.1**, *Shoreline Public Use*, **TA 14**, Recreation, for additional information on recreational activities.

Higher water temperature can elevate eutrophic conditions by stimulating nutrient release from lake sediments, increasing the rate of bacterial activity, and more easily converting nutrients into forms used by algae (Havens 2012; Wang et al. 2023). In Lake Mead in 2015, increased inflow temperature contributed to a harmful algal bloom caused by the freshwater cyanobacteria, *Microcystis*, which can produce toxins harmful to humans, pets, and wildlife (Reclamation 2016).

Releases from Glen Canyon Dam and downstream Colorado River waters are generally low in nutrients (for example, the Glen Canyon Dam phosphorus releases average 0.005 mg/L; Deemer et al. 2023). Tributary inflows (for example, Paria River and Little Colorado River) typically contain higher levels of nutrients than the mainstem Colorado River (Reclamation 2016), but overall appear to contribute relatively little to overall nutrient concentrations.

In Lake Mead, water within Las Vegas Bay has the highest concentration of nutrients due to the discharges of highly treated wastewater from the Las Vegas metropolitan area. Wastewater is a persistent contributor of phosphorus, whereas stormwater with higher phosphorus contributions is an acute contributor but a minor source overall given the infrequency of storm events. Since phosphorus is a limiting nutrient in the Colorado River system, these contributions support algal growth (USGS 2012). Lowering reservoir levels could increase the concentration of nutrients and temperatures, especially in shallow areas, which could be more favorable for algal growth (Hannoun et al. 2022).

Lake Powell is a low nutrient, oligotrophic[3] waterbody. Preliminary analyses of long-term trends in limnological data reveal a directional change in several parameters in Lake Powell in recent decades (Deemer et al. 2023). These initial data analyses suggest an increase in surface phytoplankton biovolume (algal biomass) that may be paired with changes in community composition and could have cascading effects on ecosystem function and water quality management. For example, cyanobacteria genera across all sites have appeared to shift considerably from the beginning of monitoring (1993–1997) compared to recent years (2017–2021). These community shifts could translate into changes in algal toxin formation and/or altered edibility for aquatic grazers. Growing occurrences of harmful algal blooms in Lake Powell could mean critical changes to Lake Powell water quality with detrimental results to human use and aquatic life. In a mixed methods literature review of assessing risk for cyanobacteria and phytoplankton with changes in water level regime, with potential application to Lake Powell and Lake Mead, cyanobacteria were significantly more likely to increase in response to decreases in water levels. The review also suggested that the prevalence of cyanobacteria increases when reservoir water levels decline, subsequently increasing the risk of cyanobacterial blooms in reservoirs undergoing more severe water level fluctuations and/or declines (Hoffman et al. 2025). See **TA 8.1.3***, Reaches,* **TA 8**, Biological Resources – Fish and Other Aquatic Species, and **TA 14.1.1***, Shoreline Public Use,* **TA 14**, Recreation, for additional information about harmful algal blooms' impacts on aquatic species and recreation.

TA 6.1.4 Dissolved Oxygen

Dissolved oxygen is a critical factor for fish health. Research on dissolved oxygen thresholds for both warmwater and coldwater fish species shows that salmonids are particularly vulnerable to low dissolved oxygen concentrations compared to warmwater species (Saari et al. 2018). Sustained dissolved oxygen levels below 3 mg/L can significantly reduce survival rates and feeding efficiency, whereas concentrations in the range of 6–9 mg/L are considered optimal for growth and survival across all life stages (EPA 1986).

Generally, Lake Powell dissolved oxygen concentrations are at their highest in the spring to early summer, when inflows are well-oxygenated and wind-induced mixing is high. Low dissolved oxygen concentrations move through the reservoir and closer to the dam during the summer into the fall because of organic matter decomposition and chemical reactions that consume oxygen. Dissolved

[3] Oligotrophic waterbodies are those with low concentrations of nutrients.

oxygen gradually increases in the winter because of the higher oxygen-carrying capacity of cold water and the natural mixing processes that occur during turnover. When water is discharged through the river outlet works, it becomes well-aerated and increases the dissolved oxygen levels in the tailwaters but only while the river outlet works are open.

Recently, dissolved oxygen levels in Lake Powell and the Glen Canyon Dam tailwaters[4] have been low compared with historical dissolved oxygen levels. This is due to a combination of low reservoir elevations and increasing reservoir age (Deemer et al. 2025). Low dissolved oxygen plumes occur in response to large sediment inputs; this is because suspended sediment creates high biological and chemical oxygen demand (that is, bacteria and other biota consuming oxygen, and chemical reactions consuming oxygen). Monsoonal activity, typically between July and September, can discharge particularly high organic matter loads from tributaries, leading to elevated oxygen demand within the reservoir. Large spring snowmelt inflows to Lake Powell can further drive down dissolved oxygen concentrations by resuspending deltaic sediments. Near the Colorado River inflow, approximately 45 meters (150 feet) of sediment has accumulated over the life of the reservoir. With lower storage conditions, the Colorado River has been carving away this sediment and creating a new path through its delta.

Low dissolved oxygen plumes can often extend the entire length of the reservoir, typically in the metalimnion due to the prevalence of interflows (Colorado River inflows denser than the surface water of Lake Powell entering the reservoir at a depth of neutral buoyancy). With lower storage conditions, penstock intakes draw from the metalimnion layer more frequently, causing low dissolved oxygen releases. The residence time in Lake Powell is also shorter for the low dissolved oxygen plumes under low lake elevations, extending the duration of low dissolved oxygen water being released from Glen Canyon Dam.

Dissolved oxygen levels below Glen Canyon Dam vary throughout the year, falling as low as 2.2 mg/L in the summer and rising as high as 9 to 10 mg/L in the spring (GCMRC 2025). This seasonal variation is due to changes in dissolved oxygen at the penstock level of Lake Powell during the year. The Colorado River dissolved oxygen increases approximately 1 mg/L between Glen Canyon Dam and Lees Ferry. This approximation can vary between negligible re-oxygenation and approximately 3 mg/L increases during very low oxygen releases during daylight hours (GCMRC 2025). Low dissolved oxygen conditions improve downstream of the Paria Riffle and Badger Rapids as the water is reaerated through whitewater action.

In Lake Mead, dissolved oxygen levels decrease in the bottom of Las Vegas Bay as a result of high decomposition of organic matter from the Las Vegas Wash. When there are greater nutrients and algae in surface water, generally more decomposition and low oxygen occur in bottom waters, assuming a stratified system. Monitoring is ongoing to determine the cause of decreased dissolved oxygen concentrations in isolated areas, but the driver is likely higher temperatures from inflows. Backwaters in embayments have little water exchange and tend to be shallower and warmer. These conditions increase the likelihood of algae blooms and issues with low dissolved oxygen conditions,

[4] Tailwater refers to waters located immediately below the dam. It is the reach of river immediately downstream of a reservoir that is heavily influenced by reservoir characteristics. Tailwaters are generally expected have water quality more similar to the reservoir compared to reaches further downstream.

or hypoxia[5] (Reclamation 2016). See **TA 10**, Terrestrial Wildlife Including Special Status Species, for information about algal blooms' effects on wildlife.

TA 6.1.5 Metals

The planning area contains sources of various metals, including selenium and mercury. Selenium and mercury are toxic to fish and wildlife and can accumulate in the food web (Walters et al. 2015).

Soluble hexavalent chromium has been detected in groundwater in two known locations in the Lower Colorado River Basin: at the former McCulloch Manufacturing Plant in Lake Havasu City, Arizona, and at the Pacific Gas and Electric Compressor Station near Needles, California. Mitigation efforts and plume monitoring are ongoing. The latest groundwater monitoring data indicate that plume migration is not occurring (California Water Boards 2022). The landowner continues to monitor the chromium associated with the former McCulloch Manufacturing Plant at Lake Havasu and Holly Avenues. Based on the latest site investigations, the groundwater chromium plume extended approximately 3,000 feet long and about 600 feet wide from the former McCulloch facility. This remained within the vicinity of the former McCulloch facility, which is several thousand feet from the Colorado River (AZDEQ 2022). Pacific Gas and Electric Company removed soils from 15 locations on federal land or where contaminants could migrate to federal land from the Pacific Gas and Electric Compressor Station and continues to remedy groundwater (AZDEQ 2024).

Within the Basin, about three million gallons of water and sediment at the Gold King Mine near Silverton, Colorado were released into Cement Creek, a tributary of the Animas River (USGS 2018). In addition to regular monitoring, additional United States Geological Survey and United States Environmental Protection Agency samples were taken to assess the quality of water quality data, and found detectable levels of heavy metals, such as antimony, arsenic, cadmium, and cobalt, in sediment and surface water samples (EPA 2017).

While there is a historical issue with heavy metals, these point sources are not a typical concern. Therefore, this was not considered further in the analysis.

TA 6.1.6 Perchlorate

Within the planning area, perchlorate contamination was linked to a groundwater plume from the Kerr McGee Chemical Company in Henderson, Nevada and mitigating the perchlorate contamination has been an ongoing effort. The Nevada Division of Environmental Protection and the Southern Nevada Water Authority show a decreasing trend in perchlorate concentrations over the last decade, especially after point source remediation efforts began in 2002 (Hannoun and Tietjen 2022). While there is a historical issue with perchlorate, this point source is not a typical concern. Therefore, this was not considered further in the analysis.

[5] Low levels of dissolved oxygen that can have detrimental effects on the ecological and economic health of affected areas.

TA 6.1.7 PFAS

Adjacent to Lake Mead, PFAS was detected in the Las Vegas Wash. PFAS in the Las Vegas Wash likely entered via municipal wastewater effluents, of which the likely main source was residential wastewater. PFAS concentrations were relatively low for the small tributary associated with a smaller urban airport, so that airport is an unlikely significant PFAS source (Thompson n.d.). Generally, as reservoir elevations decrease, the dilution capacity of reservoirs like Lake Powell and Lake Mead would also decrease. Decreased dilution capacity from lower reservoir elevations could result in greater concentrations of pollutants of concern, such as PFAS.

TA 6.2 Environmental Consequences

TA 6.2.1 Methodology

The analysis methodology for water quality is based on a combination of Decision Making under Deep Uncertainty (DMDU); Colorado River Simulation System (CRSS); Grand Canyon Monitoring and Research Center Dissolved Oxygen & Temperature Models for Glen Canyon, Lees Ferry, and Grand Canyon; Southern Nevada Water Authority's Lake Mead Model; Southern Nevada Water Authority's Machine Learning Model, and qualitative analysis.

The CRSS model simulates Colorado River Basin conditions decades into the future and can account for hydrological uncertainty. The CRSS model is a monthly time-step model that produces reservoir elevations, dam releases, and salinity concentrations. The CRSS model does not consider potential decreases in calcium carbonate precipitation (that is, the mechanism by which Lake Powell reduces the downstream transport of salt on annual to decadal time scales) that might occur at lower reservoir elevations when residence time is lower. Refer to **Appendix A**, CRSS Model Documentation, for more details on model documentation.

In this section, salinity is analyzed as it relates to the salinity criteria set by the Colorado River Salinity Control Forum. For information on salinity concentration and salinity related to the potential effects on resources in the International Border Region, see **Appendix M**, International Border Region of the Colorado River.

Impacts on water quality are described using conditional box plots and vulnerability bar plots based on CRSS model outputs, Grand Canyon Monitoring and Research Center models, and the Southern Nevada Water Authority's Full 3D Model and Machine Learning models. Refer to **Chapter 3** for additional information on interpreting the DMDU robustness heat maps and vulnerability bar plots.

Decision Making Under Deep Uncertainty Modeling

To assess future alternatives and management strategies, a modeling analysis known as DMDU was applied to systematically evaluate potential system responses across a wide range of plausible futures. The analysis incorporated five alternative scenarios (No Action, Basic Coordination, Enhanced Coordination, Maximum Operational Flexibility, and Supply Driven Alternatives) representing various flow conditions and the continuation of the current flow management strategies from Lake Powell (Continued Current Strategies [CCS] Comparative Baseline). These alternative scenarios are designed to span a broad spectrum of uncertainty, allowing examination of impacts on resources under several alternatives and baseline conditions. By comparing outcomes across these alternative futures, DMDU quantifies water quality impacts compared to historic conditions, with data interpretation (for example, reservoir elevation and flow conditions by alternative). If an alternative achieves a robustness score of 90 percent or higher, it can be considered truly robust with respect to a particular resource. When the difference in robustness between alternatives exceeds 10 percent, one alternative can be considered more robust than another. If the difference is less than 10 percent, the alternatives are considered similarly robust. Models were considered based on a multiagency cooperation of resource impacts.

DMDU figures are presented to provide comprehensive and reliable information about potential system outcomes under each alternative, regardless of future uncertainties. By intentionally disconnecting the analysis from probabilistic interpretation, these figures focus attention on key resource concerns and improve our understanding of how each alternative performs across a range of hydrologic conditions and are presented to provide comprehensive and reliable information about potential system outcomes under each alternative, regardless of future uncertainties. By intentionally disconnecting the analysis from probabilistic interpretation, these figures focus attention on key resource concerns and improve our understanding of how each alternative performs across a range of hydrologic conditions.

Robustness Heat Maps

Robustness heat maps evaluate how each alternative performs across a wide range of future scenarios over extended modeling periods, such as decades or the entire simulation horizon (2027–2060). Unlike conditional boxplots, which assess each year independently, heat maps aggregate results according to resource-specific definitions of "acceptability," using thresholds and frequencies to classify scenarios as successful or not. Each alternative is assigned a robustness score, indicating the percentage of futures where performance criteria are met, with higher scores reflecting greater robustness. The heat maps display multiple levels of performance, from the most challenging criteria at the top to the least stringent at the bottom, and use a highlighted row to emphasize key acceptability thresholds or significant comparison points. This color-coded format distills complex modeling results into an accessible, comparative framework, enabling readers to quickly compare alternatives, understand their relative robustness, and make informed decisions.

Vulnerability Bar Plots

Vulnerability bar plots display, for each alternative, the hydrologic conditions, based on a key Lees Ferry natural flow statistic, under which threshold outcomes are classified as preferred minimum performance (blue) or undesirable performance (red), such as during the worst 10-year drought. This visual division highlights the specific scenarios that lead to vulnerability, with larger blue regions indicating greater robustness. Accompanying boxplots provide context by relating these vulnerability thresholds to recent observations and a wide range of plausible future scenarios. The primary purpose of the vulnerability bar plot is to clarify the conditions under which an alternative is likely to fail and to determine whether those conditions fall within the range of what can reasonably be anticipated, thus informing decision-makers about each alternative's limits and resilience.

Grand Canyon Monitoring and Research Center Dissolved Oxygen and Temperature Models for Glen Canyon, Lees Ferry, and Grand Canyon

Dissolved Oxygen Model

Generalized linear mixed models were constructed to predict metalimnion dissolved oxygen content at the reservoir forebay (site name "Wahweap" LPCR0024). 176 water quality profiles were used from July, August, September, and October 1967–2023 to calculate the mean metalimnion dissolved oxygen concentration. Profiles were generally collected monthly at Wahweap, although some data gaps exist. Prior to 2010, water quality profiles were conducted by manually taking a reading every time one of the water quality parameters changed by a predetermined amount. After October 2010, a 4-Hertz profiler was used to collect measurements in continuous mode and bin data into 0.5-meter increments. The metalimnion depth in Lake Powell can vary widely, with deeper and more diffused metalimnions in years with large spring inflows. Dissolved oxygen concentrations were averaged between 7- and 50-meter, taking a broad definition of the metalimnion to encompass the order of magnitude differences observed in spring inflow volume (Deemer et al. 2025; Deemer et al. 2026).

Generalized linear mixed models were built to predict dissolved oxygen concentrations as a function of day of year, minimum reservoir elevation in that year, volume of spring inflow (calculated as total inflow from April to July), reservoir age (calculated in years since 1963), and 3 interaction terms: age by elevation, spring inflow by elevation, and age by spring inflow interaction with year as a random effect. Metalimnion water temperatures were positively correlated with the volume of the spring inflow (Pearson correlation = 0.61), so water temperature was not included in modeling efforts, given its weaker relationship to mean metalimnion dissolved oxygen concentration. At a yearly scale, the Pearson correlation between inflow and mean dissolved oxygen was −0.26, whereas the Pearson correlation between water temperature and mean dissolved oxygen was −0.19. Before modeling, all noninteractive predictors were standardized by subtracting the mean predictor value and dividing by the standard deviation of the predictor value. Interactions were then calculated as the product of the standardized predictors. Day of year was represented as the calendar day (183–304) standardized. The standardized calendar day was then squared for a second predictor term. Modeling was done in R 4.3.0 (R Core Team 2020) using the lmer function, and best models were selected based on Akaike information criterion values and a priori 2-stage buildup model selection strategy. All main effects were considered in the first stage, and any models within 5 Akaike information criterion of the best model were carried forward, and in the second stage all potential 2-way interactions among main effects selected in the first stage were considered as additions to the models identified in the first stage (Deemer et al. 2025; Deemer et al. 2026).

To test for monsoonal influence on reservoir dissolved oxygen concentrations, a proxy for local monsoon activity was developed using daily discharge data from July, August, and September from the Paria River near Kanab, Utah (gage 09381800); the Escalante River near Escalante, Utah (gage 09337500); Chinle Creek near Mexican Water, Arizona (gage 09379200); the San Rafael River near the Green River, Utah (gage 09328500); and the Dirty Devil River Above Poison Springs Wash near Hanksville, Utah (gage 09333500) from 1980 to 2023. The 43-year average monsoon (July to September) flow at these sites varied from 0.23 cubic meters per second at the Escalante to 2.59 cubic meters per second at the San Rafael. Flows were normalized from all gages to the average flow across all gages (1.39 cubic meters per second) by multiplying each daily discharge measurement by 1.39 and dividing by the site-specific long-term average. The mean normalized daily flow was then calculated during July, August, and September across the 5 gages. The described generalized linear mixed modeling model selection strategy was repeated with this added monsoonal predictor using the subset of the data from 1980 forward (Deemer et al. 2025; Deemer et al. 2026).

Following the same procedure as for the reservoir forebay, generalized linear mixed models were constructed to predict metalimnion dissolved oxygen concentration at six additional sites within Lake Powell with at least 40 separate years of available profile data from at least 1 month spanning July to October. Five of the six sites were on the Colorado River arm, and one site was on the San Juan River arm of Lake Powell (Deemer et al. 2025; Deemer et al. 2026).

To support predictive modeling of dissolved oxygen in dam releases, six depth-specific models of monthly metalimnion dissolved in the reservoir forebay were constructed using the same model selection approach described earlier. Models were set up to predict dissolved oxygen in 10-meter depth bins starting 6 meters below the reservoir surface and extending down to 66-meters. Instead of predicting mean dissolved oxygen across the period, the models were set to predict the minimum monthly means, given concern over the minimum dissolved oxygen levels that may be released through the dam to the tailwater. The models can then be combined with reservoir elevation information and the associated depth of the penstock water release structures to predict the likelihood that dissolved oxygen concentrations will drop below threshold values each season. The probability of falling below a particular threshold was then determined from the cumulative probability distribution described by a predicted minimum and the estimated standard deviation associated with a model (that is, ignoring parameter uncertainty, a relatively small source of error; Deemer et al. 2025; Deemer et al. 2026).

Water Temperature Model

The Dibble et al. 2020 water temperature model, an equilibrium temperature model with empirically estimated parameters, was developed by fitting relationships to monthly average water temperature data collected from 1985 to 2015 at 44 gages along the Colorado, Gunnison, Green, Yampa, Duchesne, White, San Juan, and Animas rivers. Solar radiation and air temperature represent the primary components in the simplified heat budget that determines river temperature. The model also accounted for major tributaries (that is, mean annual flow ≥10 percent of the mainstem river). To estimate model suitability, the model was first fit to data from odd years. Data from even years were used to calculate the root mean square error and overall bias of out-of-sample prediction aggregated by river segment and month of year. Then, the model was fit using all data, producing estimates with similar means but higher precision. The estimates were used to predict water temperatures for the current period (1985 to 2015) at a 1-river-kilometer resolution along 2,560 river-kilometer of river (Dibble 2020).

Future water temperature scenarios were determined by using air temperature predictions from phases 3 and 5 of the Coupled Model Intercomparison Project models to understand how air temperatures may change by mid-century (2040 to 2059) relative to 1950 to 1999. On average, air temperatures in the Basin are predicted to increase by 1.85 to 3.01 °C per month by mid-century, averaging approximately 2.6 °C on an annual basis. An annual air temperature increase of approximately 2.6 °C would reduce mean annual flow in the Basin by approximately 17 percent through greater evaporation, evapotranspiration, and sublimation, among others. Inputs into the model considering climate only used predicted increases in monthly air temperature, combined with predicted declines in Colorado River flow. Inputs into the storage plus climate scenario used nonlinear regression (least squares) to predict reservoir release temperatures as a function of storage elevation by month, which permitted an assessment of the degree to which changes in reservoir storage affect riverine thermal regimes relative to warming alone. This analysis included data spanning 1965 to 2015 from five large storage reservoirs in the Basin (Fontenelle, Flaming Gorge, Navajo, Glen Canyon, and Hoover). The predicted water temperature associated with the lowest recorded storage elevation for each reservoir was used to predict potential warming of releases if storage was deemphasized. As such, the low storage adjustment represents predicted river temperature at the lowest storage after reservoirs initially filled relative to the base model (Dibble 2020).

The Eppeheimer et al., 2025 water temperature model includes the segment of the Colorado River flowing through Glen, Marble, and Grand canyons in Arizona that is bounded by Lake Powell and Lake Mead. Water from the upstream Lake Powell is released through Glen Canyon Dam and flows approximately 475 river-kilometers before entering Lake Mead. Riverine environmental conditions and aquatic communities change dramatically over its length. A dam tailwater segment is located in the first 25 river-kilometers downstream of Glen Canyon Dam and is characterized by clear water, abundant aquatic vegetation, and water temperatures almost entirely determined by reservoir release temperatures. Water temperature is measured every 15 minutes near the bottom of this river segment at the Lees Ferry gage (United States Geological Survey gage: 09380000) near the location of Lee Ferry that demarcates the Upper and Lower Colorado River Basins. Since 1973, the tailwater segment was characterized by three decades of very cold water temperatures (95 percent range of daily water temperatures: 7.6 to 11.3 °C at the Lees Ferry gage), followed by approximately two decades of cool water temperatures prior to 2022 (95 percent range of daily water temperatures: 8.1 to 14.3 °C at the Lees Ferry gage) and was managed as a blue-ribbon rainbow trout fishery. Downstream from the tailwater segment and the Lees Ferry gage, the river becomes more turbid, aquatic vegetation becomes rare, and water temperatures gradually warm in the summer. Approximately 122 river-kilometers downstream from the Glen Canyon Dam, the Colorado River reaches its confluence with the Little Colorado River, a tributary that was once the only spawning site for humpback chub, and is currently a population center for humpback chub in Grand Canyon. Further downriver, the humpback chub population has increased dramatically over the last decade in a river segment approximately 200 river-kilometers in length. This river segment is frequently referred to as the western Grand Canyon and is approximately centered on the confluence of the Colorado River with Diamond Creek (approximately 386 river-kilometers downstream from Glen Canyon Dam). The two models separately estimate small-mouth bass propagule pressure from Lake Powell to the tail-water segment and the potential for smallmouth bass population growth based on Colorado River temperatures at the Lees Ferry gage, the Little Colorado River confluence, and the Diamond Creek confluence (Eppeheimer et al. 2025).

The model estimated smallmouth bass propagule pressure from Lake Powell by modeling rates of fish passage through Glen Canyon Dam which were assumed to be a function of (1) Lake Powell elevation, (2) predicted river temperatures by fitting and forecasting from a novel model of Glen Canyon Dam release temperatures combined with a previously published model of river warming below Glen Canyon Dam, and (3) estimated the probability of smallmouth bass asymptotic population growth exceeding one under various scenarios based on predicted daily average water temperatures and a matrix model (Eppeheimer et al. 2025).

Glen Canyon Dam can release water through penstocks and river outlets. Typically, water is passed through the penstocks at a centerline elevation of 3,470 feet to generate hydropower; turbines likely cause high mortality but do not prevent successful fish passage. Water can also be released through the deeper river outlets (centerline of 3,370 feet). However, the river outlets do not generate hydropower, so their use is rare. Results presented here assume all water is passed through the penstocks until reservoir elevations are at or below 3,490 feet, at which point releases switch to river outlets to avoid damaging hydropower infrastructure. Both the smallmouth bass propagule pressure and smallmouth bass population growth models rely on Lake Powell elevations, which we estimated using a water resource operations model used by Basin managers. In the water resource operations model, changes in Lake Powell elevation are modelled monthly as a function of starting elevation, inflows, outflows, bank storage, and evaporative losses. A range of future conditions was considered using combinations of starting elevations at the beginning of a year, annual inflows, and annual outflows. We considered starting elevations ranging from 3,470 (18 percent of capacity) to 3,600 feet (50 percent of capacity). Inflows were based on resampling the past 23 years (2000–2022). Inflows during this period varied from 4 to 15 million acre-feet (maf) per year. In our analyses, we assumed one of two scenarios for annual outflows: (1) 7.48 maf per year outflows with monthly patterns derived from Reclamation's projections (these are the anticipated outflows for the near-term based on current water management agreements) and (2) a potential management scenario in which reservoir levels are held constant over the course of a year by matching monthly dam release volumes with monthly inflow volumes (this scenario will be referred to as "maintain elevation"). We also produced forecasts for 2025 using the 2025 calendar year projected Lake Powell starting elevation of 3,572 feet, 2025 predicted outflows as of October 2024, and 23 historic inflow traces (2000 to 2022) characterizing inflow variability (Eppeheimer et al. 2025).

Southern Nevada Water Authority's Lake Mead Model

The Southern Nevada Water Authority maintains a three-dimensional hydrodynamic and water quality model for Lake Mead that is used to simulate probable future scenarios and aid in management decisions. This model is implemented in Aquatic Ecosystem Model 3D, which simulates lakes, estuaries, and reservoirs by solving the Reynolds-averaged Navier–Stokes equations with a turbulent eddy closure and wind-forced mixing model. The TRIM-3D method is the numerical scheme utilized by Aquatic Ecosystem Model 3D and was chosen for its stability and ability to conserve mass, with the added benefit of computational efficiency. The model uses a rectangular x-y grid, with the ability to vary layer thickness in the z direction. Aquatic Ecosystem Model 3D solves for vector values on the faces of each grid cell, and transported scalars at the center of each grid cell. Transported scalars can include, but are not limited to, temperature, dissolved oxygen, conductivity, chlorophyll a, suspended sediment, conservative and decay tracers, zooplankton, phytoplankton, and chemical parameters such as phosphorus, nitrogen, and carbon. Particle dynamics in Aquatic Ecosystem Model 3D are simulated using a balance equation, which considers the effects of settling, resuspension, advection, mixing, and boundary forcing. Aquatic Ecosystem Model 3D is widely used by lake managers and water utilities as a future planning tool as it allows researchers to simulate projected conditions under projected future operating scenarios (Hannoun et al. 2021).

The Lake Mead Model Cartesian grid is based on lake bathymetry and is assumed to have little change over time as most inflow into Lake Mead is from highly-managed upstream Glen Canyon Dam. A bathymetry study showed that Lake Mead had a small increase in available volume between the beginning of Glen Canyon Dam's operations in 1963 and 2001 when the survey was conducted due to the sediment-blocking ability of Glen Canyon Dam (Hannoun et al. 2021).

The model uses a 300 by 300-meter grid with depth outputs every 2 meters and contains over 210,000 wetted cells at the 1100 feet Lake Mead elevation. The lake bathymetry is varied, and a single cell shows the large area of the grid. The model inflows are the Colorado River, which accounts for 97 percent of the inflow volume, with the remaining inflow divided between the Virgin and Muddy Rivers and the Las Vegas Wash. Most outflow is released through the Hoover Dam, with minor withdrawals from Southern Nevada Drinking Water Authority's drinking water intake. Meteorological parameters are input into the model as boundary forcing values. The Lake Mead Model was calibrated to measured data to ensure model accuracy and minimization of error as a future planning tool, and the Lake Mead Model provides an excellent fit to collected field data (Hannoun et al. 2021).

The Aquatic Ecosystem Model 3D model requires hundreds of physical parameters to operate. Previously published studies utilizing Aquatic Ecosystem Model 3D include a priori “uncalibrated” studies where parameters from literature are used to simulate and validate lake processes. These studies all provide excellent agreement with collected field data; however, site-specific calibrations are appropriate when time series data are available. In this study, an amalgamation of site-specific calibrated parameters as well as literature values are used in accordance with available field data. First, a derivative sensitivity analysis as used to determine hydrodynamic parameters that produce large changes in model output. Past studies have identified how meteorological forcing values affect thermal outputs; however, recent studies in lake modeling have sought to identify and optimize internal model parameters. For the Lake Mead Model, the identified sensitive parameters (that is, mean albedo, the surface heat transfer coefficient, and the wind shear coefficient) were optimized using a nonlinear least squares method (Hannoun et al. 2021).

The nonlinear least squares solver used to perform this optimization was MATLAB's[6] nonlinear least squares function, which utilizes a Levenberg–Marquardt algorithm to minimize the residual between model output and collected field data. Temperature profiles were used to validate the model and present an exemplary fit to the collected field data (Hannoun et al. 2021).

Impact Analysis Area

The analysis area for water quality is the geographic and temporal scope introduced in **Section 3.2**. Due to the data available, analysis was limited to surface water quality.

Assumptions

- There will be modifications in quantity, timing, temperature, and quality of water released from Glen Canyon Dam and Hoover Dam.

[6] MATLAB is a computing platform that is used for engineering and scientific applications like data analysis, signal and image processing, control systems, wireless communications, and robotics.

Impact Indicators

- Salinity
- Temperature
- Dissolved oxygen
- Reservoir elevation
- Dilution capacity

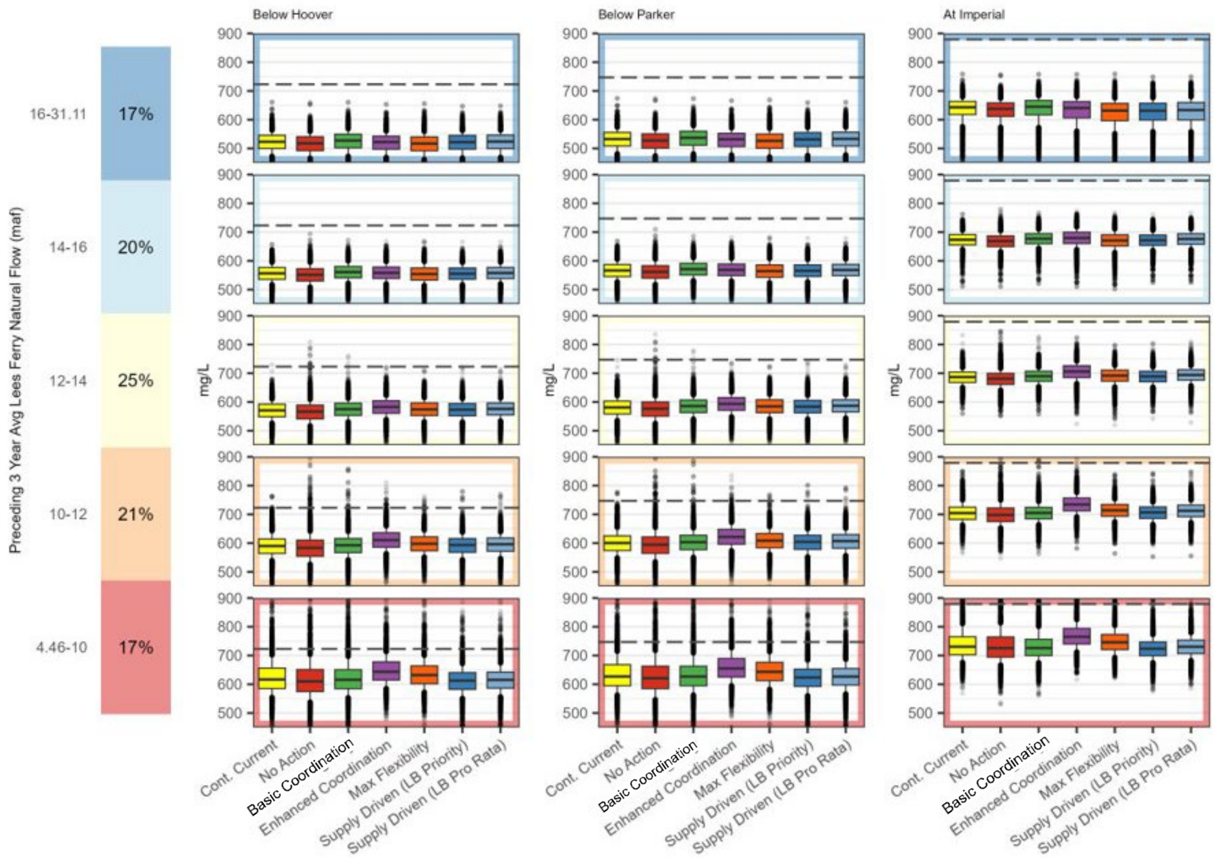
TA 6.2.2 Issue 1: How would reservoir storage, reservoir releases, and corresponding changes in river flows downstream of the reservoirs affect salinity?

Increased salinity concentrations from human activities pose a threat to drinking water, irrigation, agricultural production, municipal water supplies, and infrastructure. Reservoirs like Lake Powell and Lake Mead influence salinity by attenuating salinity transport downstream and possibly acting as a source or a sink (Deemer et al. 2020). Reservoirs also modulate the downstream transport of salinity (Deemer et al. 2020) by reducing the baseflow peaks in salinity and increasing the snowmelt troughs (Deemer et al. 2020; Moody and Mueller 1984). On an annual timescale or longer, reservoirs have been found to reduce salinity (for example, a 10 percent reduction in downstream total dissolved solids (TDS) for Lake Powell, Deemer et al. 2020), although the extent to which this effect applies to other Colorado River Basin reservoirs is unknown. Dam releases are typically from deeper in the water column and generally have elevated salinity concentrations relative to surface waters. As reservoir water levels drop, reservoir salinity can often increase (Zohary and Ostrovsky 2011).

Figure TA 6-4 shows simulated salinity concentrations below Hoover Dam, below Parker Dam, and at Imperial Dam under various hydrologic conditions. Hydrologic conditions are divided into the preceding 3-year natural flow groups, see **Chapter 3, Figure 3-1** for more information. For comparison against the Colorado River Basin Salinity Control Forum's salinity water quality standards, the figure displays a dashed line representing the salinity thresholds below Hoover Dam, below Parker Dam, and at Imperial Dam[7] (that is, 723 mg/L, 747 mg/L, and 879 mg/L, respectively). The figure also shows the simulated salinity concentrations at each site under various hydrologic conditions.

[7] The Colorado River Basin Salinity Control Forum does not have a water quality standard for Glen Canyon Dam; therefore, Glen Canyon Dam was not included in this analysis.

Figure TA 6-4
Annual Flow-Weighted Average Salinity Concentrations



Note: Supply Driven LB Priority and Supply Driven LB Pro Rata results differ primarily because of how the two shortage-distribution approaches interact with the modeled assumptions governing the storage and delivery of conserved water (see **Appendix B**, Modeling Assumptions: Lake Powell and Lake Mead Storage and Delivery of Conserved Water).

Figure TA 6-4 shows that no simulated annual flow-weighted average salinity concentrations under any alternatives would exceed the salinity thresholds under the Wet and Moderately Wet Categories (16–31.1 maf and 14–16 maf, respectively). As conditions get drier, a greater number of the highest simulated annual flow-weighted average salinity concentrations exceed the salinity threshold at the different sites. However, overall, the interquartile range (the middle half of the outputs, including the median) under all alternatives did not exceed the salinity criteria under any of the hydrology conditions. Therefore, a majority (90 percent or greater) of simulated futures did not exceed the salinity criteria in even the most challenging hydrologic conditions. **Table TA 6-2** below visualizes the upper extremes of the outputs shown in **Figure TA 6-4**. The table depicts the maximum and 90th percentile values shown in the figure.

Table TA 6-2
Annual Flow-Weighted Average Salinity Concentrations Below Hoover Dam*

Alternative	Flow Category (maf)	Maximum** (mg/L)	90%*** (mg/L)
CCS Comparative Baseline	12-14 (Average Flow)	730	610
CCS Comparative Baseline	10-12 (Dry Flow)	763	642
CCS Comparative Baseline	4.46-10 (Critically Dry Flow)	956	701
No Action	12-14 (Average Flow)	809	609
No Action	10-12 (Dry Flow)	897	641
No Action	4.46-10 (Critically Dry Flow)	1295	703
Basic Coordination	12-14 (Average Flow)	761	613
Basic Coordination	10-12 (Dry Flow)	858	640
Basic Coordination	4.46-10 (Critically Dry Flow)	1325	696
Enhanced Coordination	12-14 (Average Flow)	720	623
Enhanced Coordination	10-12 (Dry Flow)	810	659
Enhanced Coordination	4.46-10 (Critically Dry Flow)	1309	713
Maximum Operational Flexibility	12-14 (Average Flow)	709	615
Maximum Operational Flexibility	10-12 (Dry Flow)	763	645
Maximum Operational Flexibility	4.46-10 (Critically Dry Flow)	1112	700
Supply Driven (LB Priority)	12-14 (Average Flow)	722	612
Supply Driven (LB Priority)	10-12 (Dry Flow)	780	637
Supply Driven (LB Priority)	4.46-10 (Critically Dry Flow)	1014	671
Supply Driven (LB Pro Rata)	12-14 (Average Flow)	714	613
Supply Driven (LB Pro Rata)	10-12 (Dry Flow)	770	639
Supply Driven (LB Pro Rata)	4.46-10 (Critically Dry Flow)	1017	673

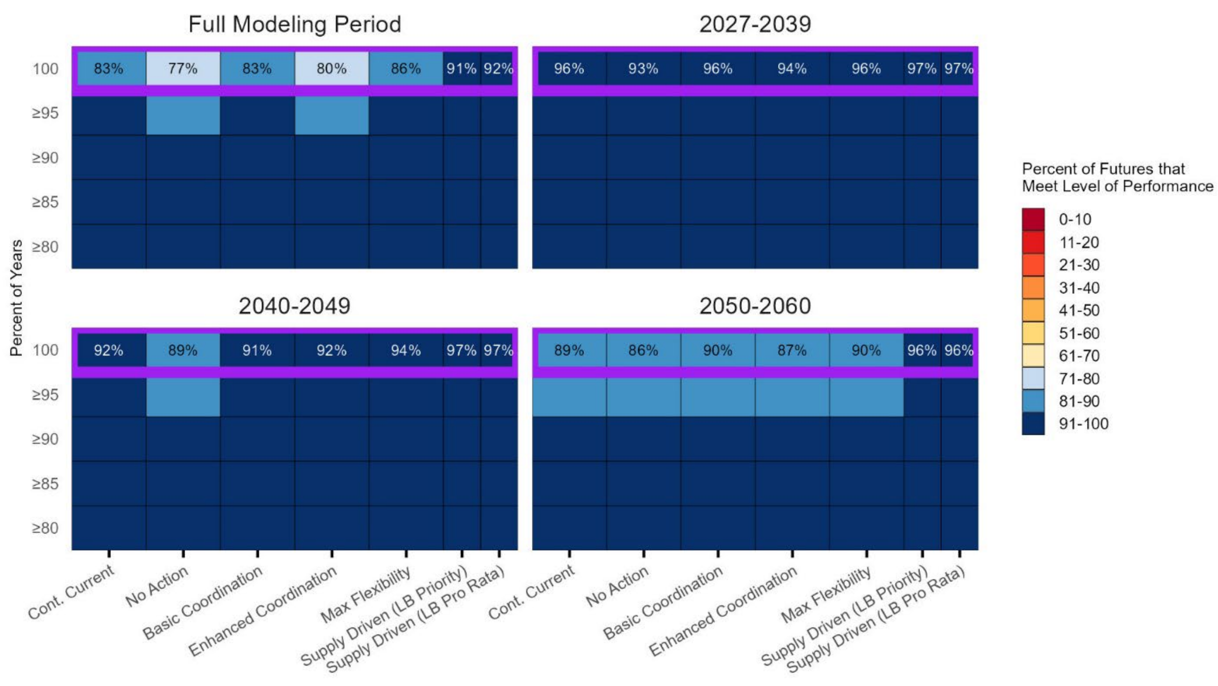
*Concentrations that are shaded where simulated salinity exceeds the water quality standard below Hoover Dam (that is, 723 mg/L).
**Maximum refers to the simulated salinity concentration that is greatest under its corresponding alternative and flow category.
**90% refers to the simulated salinity concentration that is higher than 90% of the total outputs under its corresponding alternative and flow category. This means that 90% of the simulated salinity concentrations in this flow category and under this alternative are lower than this value.

As shown in **Figure TA 6-4** and **Table TA 6-2**, under the Average Flow Category (12–14 maf), the maximum simulated annual flow-weighted salinity concentrations under the CCS Comparative Baseline and the No Action and Basic Coordination Alternatives exceeded the salinity threshold below Hoover Dam. The maximum simulated annual flow-weighted salinity concentration under the Enhanced Coordination, Maximum Operational Flexibility, and Supply Driven Alternatives (both the Lower Basin [LB] Priority and LB Pro Rata approaches) did not exceed the salinity threshold under the Average Flow Category.

Across all alternatives, simulated annual flow-weighted salinity concentrations were greatest under the Critically Dry Flow Category (4.46–10 maf), due in part to the low reservoir elevations and low inflow associated with these hydrologic conditions. Under the Critically Dry Flow Category, simulated average flow-weighted average salinity concentration upper extremes exceed the salinity thresholds at all sites under all alternatives. The Enhanced Coordination and Maximum Operational Flexibility Alternatives had the greatest median values, although these median values do not exceed the salinity threshold.

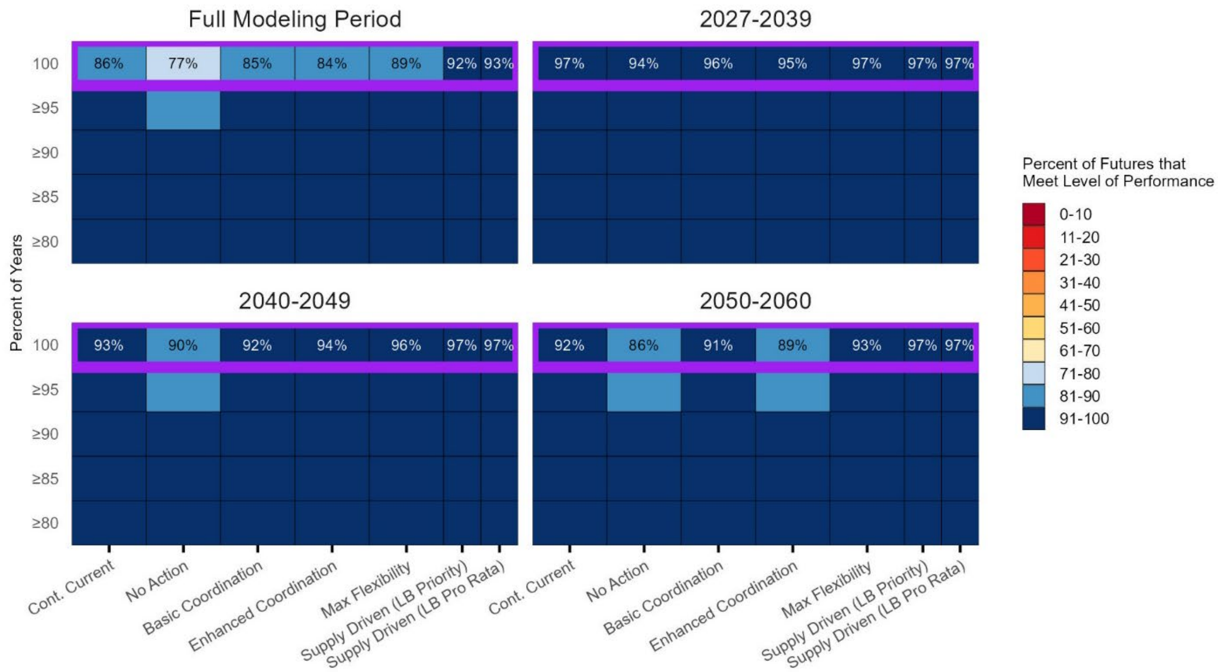
In reviewing robustness (**Figure TA 6-5**, **Figure TA 6-6**, and **Figure TA 6-7**), the simulated salinity concentrations were less than the salinity threshold for a majority of futures under all alternatives over the full modeling period. **Figure TA 6-5** also shows that below Hoover Dam, all alternatives, except the Supply Driven Alternatives (both LB Priority and LB Pro Rata approaches), exceeded the salinity criteria over a greater percentage of futures in later modeling periods (2040–2049 and 2050–2060). The greatest percentage of futures exceeded the salinity threshold under the No Action Alternative (23 percent) over the full modeling period. However, most simulated futures did not exceed the salinity thresholds under all alternatives.

Figure TA 6-5
Salinity Below Hoover: Robustness.
Percent of futures in which the salinity concentration is less than 723 mg/L in the percent of years specified in each row



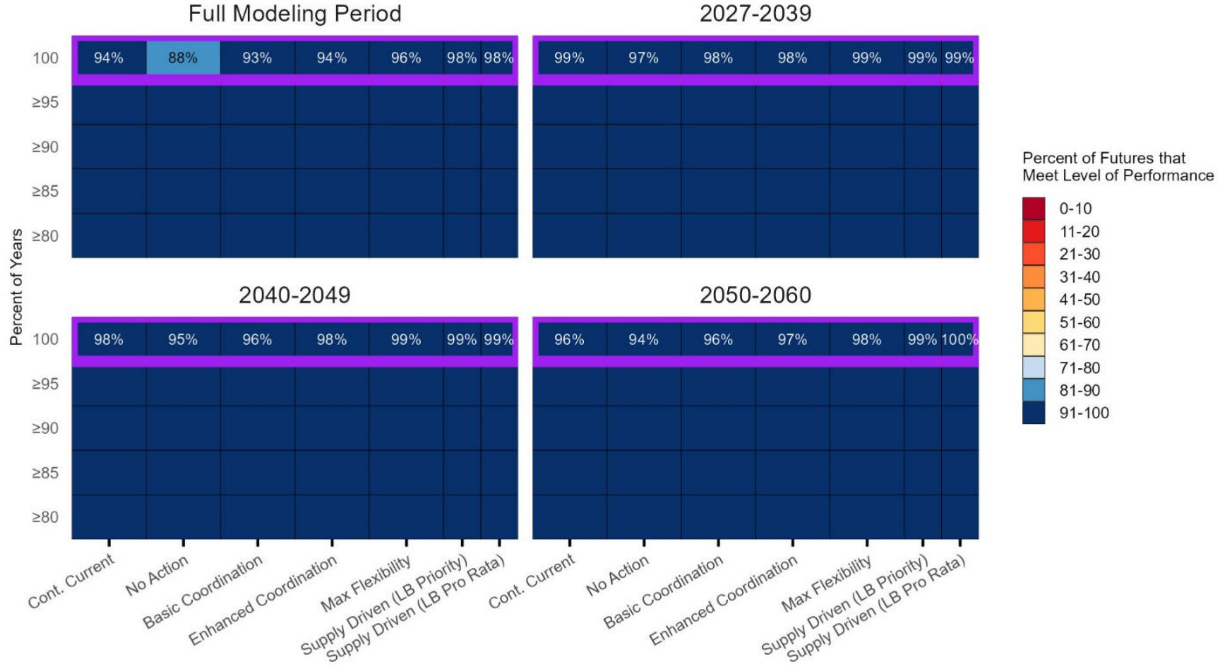
Note: Supply Driven LB Priority and Supply Driven LB Pro Rata results differ primarily because of how the two shortage-distribution approaches interact with the modeled assumptions governing the storage and delivery of conserved water (see **Appendix B**, Modeling Assumptions: Lake Powell and Lake Mead Storage and Delivery of Conserved Water).

Figure TA 6-6
Salinity Below Parker: Robustness.
Percent of futures in which the salinity concentration is less than 747 mg/L in the percent of years specified in each row



Note: Supply Driven LB Priority and Supply Driven LB Pro Rata results differ primarily because of how the two shortage-distribution approaches interact with the modeled assumptions governing the storage and delivery of conserved water (see **Appendix B**, Modeling Assumptions: Lake Powell and Lake Mead Storage and Delivery of Conserved Water).

Figure TA 6-7
Salinity at Imperial: Robustness.
Percent of futures in which the salinity concentration is less than 747 mg/L in the percent of years specified in each row

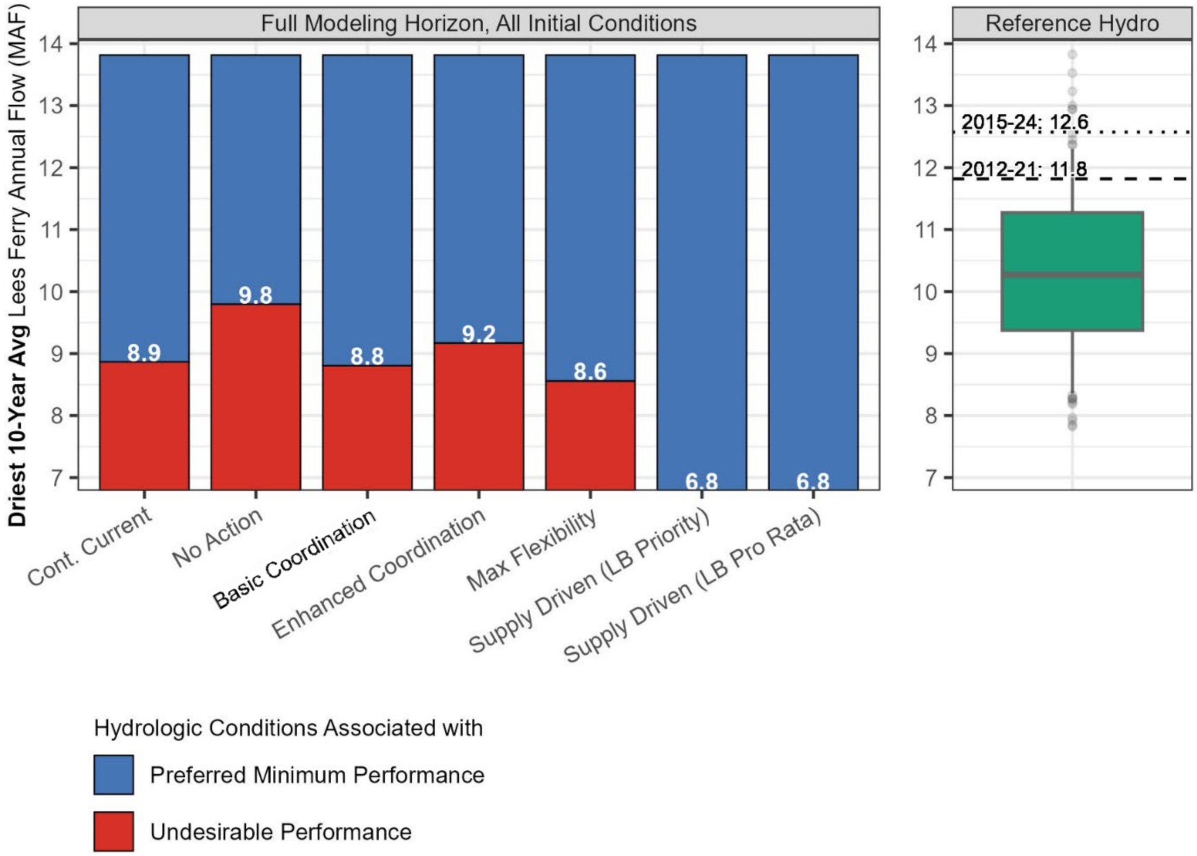


Note: Supply Driven LB Priority and Supply Driven LB Pro Rata results differ primarily because of how the two shortage-distribution approaches interact with the modeled assumptions governing the storage and delivery of conserved water (see **Appendix B**, Modeling Assumptions: Lake Powell and Lake Mead Storage and Delivery of Conserved Water).

It can be inferred that the annual flow-weighted salinity concentrations below Parker Dam and at Imperial Dam are correlated with those below Hoover Dam, as the median salinity values and interquartile ranges consistently increase as hydrologic conditions get drier and follow a similar pattern across all alternatives in **Figure TA 6-4**.

Since the salinity below Parker Dam and at Imperial Dam correlates closely with the simulated salinity concentrations below Hoover Dam, a vulnerability analysis was completed for salinity below Hoover Dam to represent all three sites, as shown in **Figure TA 6-8**. The distribution of driest 10-year average volumes in the reference hydrology is shown on the right side of the vulnerability bar plot. The reference hydrology's median value is 10.3 maf, and the most recent 10-year average Lees Ferry annual flow (12.6 maf from 2015–2024) is represented by a dotted line for comparison. In the reference hydrology panel, the worst observation of the driest 10-year average Lees Ferry annual flow is 11.8 maf from 2012–2021, which is represented by a dashed line.

Figure TA 6-8
Salinity at Hoover: Vulnerability.
Conditions that Could Cause Salinity Below Hoover Above 723 mg/L in 1 or More Years.



Under all alternatives, the hydrologic conditions associated with undesirable performance (exceeding the 723 mg/L salinity threshold below Hoover Dam) are less than the median reference hydrology conditions (that is, 10.3 maf). The hydrologic conditions associated with undesirable performance for all alternatives, except the No Action Alternative (9.8 maf), are also below the 25th percentile of observed hydrology in the reference ensemble (9.4 maf). Further, the hydrologic conditions associated with undesirable performance for the Supply Driven Alternatives (both LB Priority and LB Pro Rata approaches) (6.8 maf), are less than any previously observed conditions in the reference hydrology (7.8 maf).

Analysis key takeaways:

- Under the Average Flow Category (12–14 maf), the maximum simulated annual flow-weighted salinity concentrations under the CCS Comparative Baseline and the No Action and Basic Coordination Alternatives exceeded the salinity threshold below Hoover Dam.

- Simulated annual flow-weighted salinity concentrations were greatest under the Critically Dry Flow Category (4.46–10 maf) under all alternatives due to the lowest reservoir elevations associated with these hydrologic conditions. Under the Critically Dry Flow Category, simulated average flow-weighted average salinity concentration upper extremes exceeded the salinity thresholds at all sites under all alternatives. Under all alternatives, a majority (90 percent or greater) of simulated futures did not exceed the salinity criteria in even the most challenging hydrologic conditions.
- Considering robustness, under all alternatives, a majority of simulated futures did not exceed the salinity criteria established by the Colorado River Basin Salinity Control Forum below Hoover Dam, below Parker Dam, or at Imperial Dam. Compared with the other alternatives, simulated futures under the No Action Alternative exceeded the salinity threshold below Hoover Dam under the highest percentage of futures (33 percent) over the full modeling period.
- Salinity for releases below Parker Dam and at Imperial Dam are highly correlated with releases below Hoover Dam.
- In a vulnerability analysis of conditions that could cause salinity concentrations below Hoover Dam to exceed 723 mg/L, the hydrologic conditions associated with undesirable performance for the No Action Alternative (9.8 maf) are less than that of the median of previously observed hydrology in the reference ensemble. The hydrologic conditions associated with undesirable performance for the Basic Coordination, Enhanced Coordination, and Maximum Operational Flexibility Alternatives are less than the 25th percentile of previously observed hydrology in the reference ensemble. Further, the hydrologic conditions associated with undesirable performance for the Supply Driven Alternatives, both LB Priority and LB Pro Rata approaches (6.8 maf), are less than that of any previously observed conditions in the reference hydrology (7.8 maf).

TA 6.2.3 Issue 2: How would reservoir storage, reservoir releases, and corresponding changes in river flows downstream of the reservoirs affect water temperature?

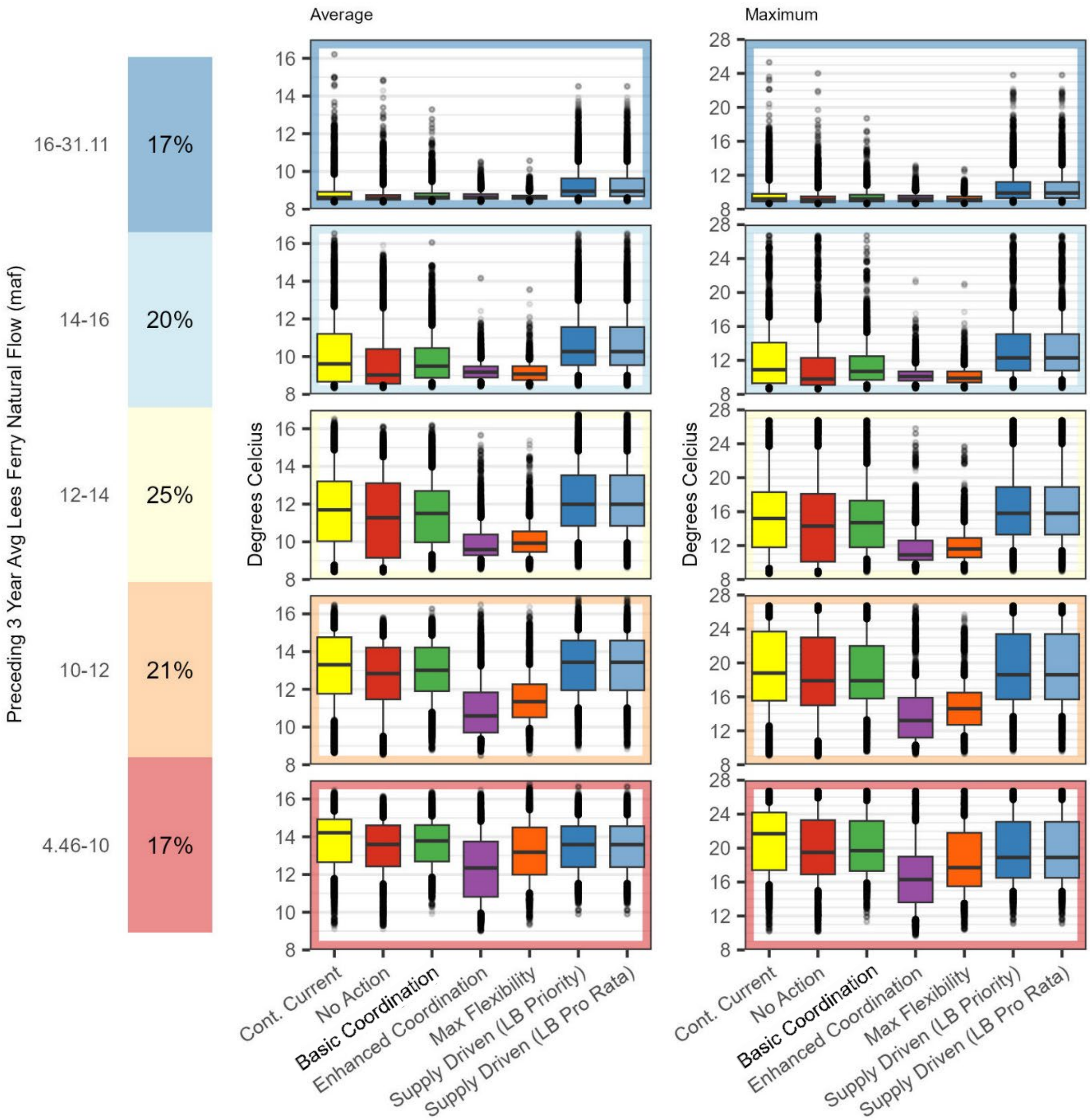
Water temperature strongly influences biological and chemical processes. For example, the temperature of dam releases affects fish population dynamics in downstream river segments, and elevated reservoir temperatures can lead to harmful algal blooms.

Sections **TA 8.2.3** and **TA 8.2.5**, **TA 8**, Biological Resources – Fish and Other Aquatic Species, describe the impacts of temperature on fish and other aquatic species at temperature thresholds of 12 °C, 16 °C, and 20 °C (53.6 °F, 60.8 °F, and 68 °F). Exceeding 12 °C (53.6 °F) creates thermal conditions that support mainstream humpback chub growth, which is a desirable response, but exceeding 16 °C (60.8 °F) improves smallmouth bass reproduction at Lees Ferry, which is an undesirable response). For trout species, exceeding the 20 °C (68 °F) threshold reduces rainbow trout survival (exceeding is an undesirable response). According to the life histories of rainbow trout and native Grand Canyon fishes, temperatures above 20 °C (68 °F) are likely to decrease rainbow trout survival while creating conditions more favorable for the growth of native fish and smallmouth bass. Additionally, warmer water temperatures may increase the competitive advantage for brown trout, as this species is more tolerant of elevated temperatures.

Figure TA 6-9 shows simulated Colorado River temperature at Lees Ferry under different hydrologic conditions by looking at the preceding 3-year average of Lees Ferry natural flows. In the Average Flow Category (12–14 maf), the median and interquartile ranges for simulated annual average of daily temperatures fell below 12 °C (53.6 °F). Under increasingly dry hydrology categories (that is, the Moderately Wet Flow Category [14-16 maf] to the Critically Dry Flow Category [4.46-10 maf]), the median values for simulated annual maximum temperatures and annual average of daily temperatures increased across alternatives. Additionally, each alternative's interquartile range increased under increasingly dry hydrology categories. As shown in **Figure TA 6-10**, alternatives trended similarly at Pearce Ferry under increasingly dry hydrology categories.

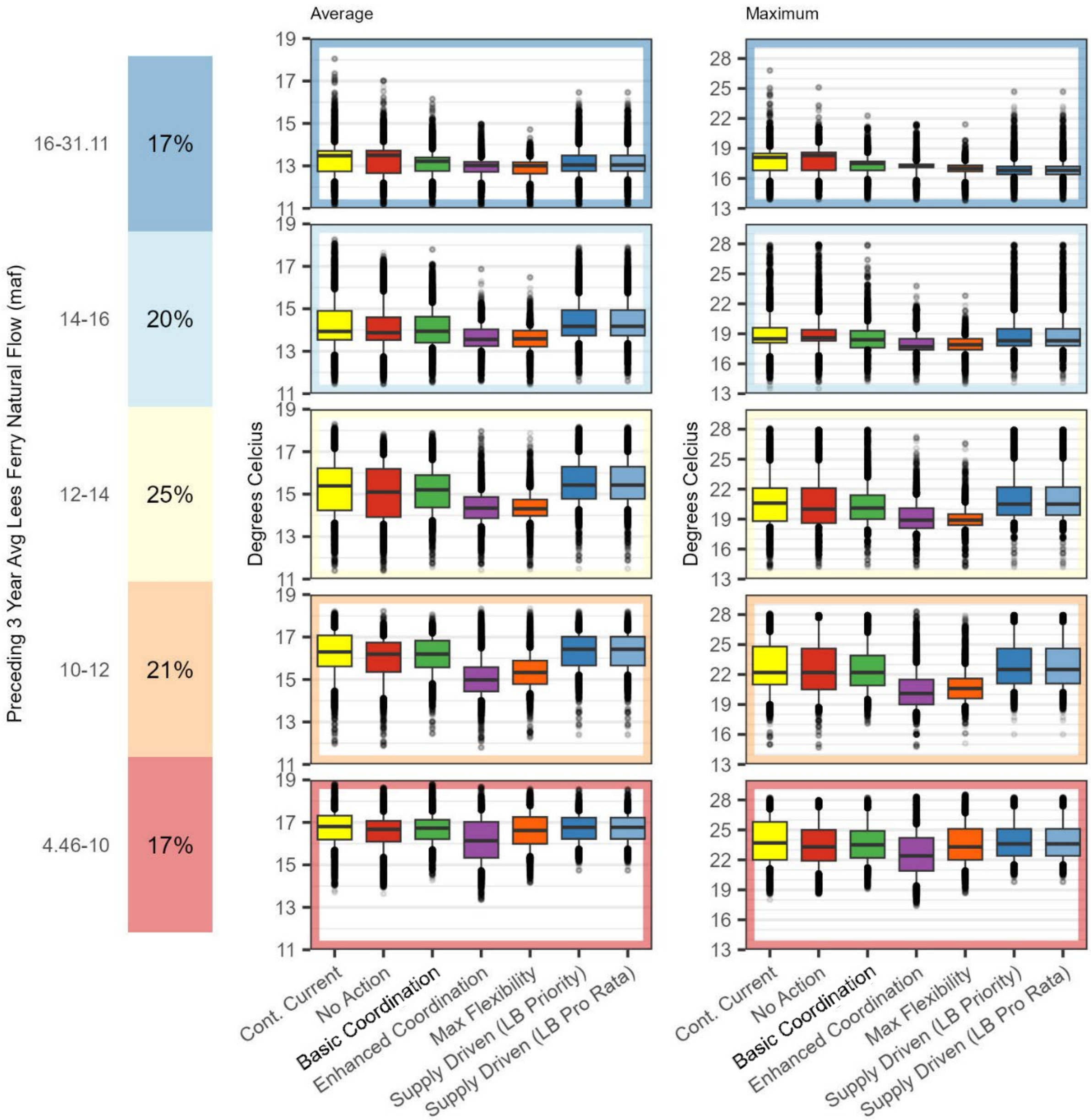
Figure TA 6-9 shows that under the driest hydrologic conditions (10–12 maf and 4.46–10 maf) at Lees Ferry, the Enhanced Coordination and Maximum Operational Flexibility Alternatives had the lowest median values for the annual average of daily temperatures and the annual maximum temperature. The Enhanced Coordination Alternative also had the largest interquartile range under dry hydrologic conditions (that is, 4.46–10 maf). Similarly, at Pearce Ferry, the Enhanced Coordination and Maximum Operational Flexibility Alternatives had the lowest median values for the annual average of daily temperatures and the annual maximum temperature, as shown in **Figure TA 6-10**.

Figure TA 6-9
Average* and Maximum Colorado River Temperature at Lees Ferry**



*Average temperature refers to the annual average of daily temperatures.
**Maximum temperature refers to the annual maximum of daily temperature.

Figure TA 6-10
Average* and Maximum Colorado River Temperature at Pearce Ferry**



*Average temperature refers to the annual average of daily temperatures.
**Maximum temperature refers to the annual maximum of daily temperature.

As shown in **Figure TA 8-9** in **TA 8.2.3**, **TA 8**, Biological Resources – Fish and Other Aquatic Resources, each temperature threshold for fish species was assessed based on the number of days in which modeled traces exceed the threshold compared to different flow regimes. For drier conditions (10–12 maf and 4.46–10 maf), simulated temperatures had higher medians and smaller interquartile ranges than the other hydrology conditions. Under the driest conditions (4.46–10 maf), temperatures are expected to exceed 12°C at a higher probability and frequency across all alternatives, with the Enhanced Coordination Alternative having the greatest interquartile range of 124.5 to 220 days.

In **TA 8.2.3**, **TA 8**, Biological Resources – Fish and Other Aquatic Resources, **Figure TA 8-10** shows the percent of futures in which water temperature does not exceed 20 °C (68 °F), which is the temperature threshold that reduces rainbow trout survival, over the full modeling period in one or more days out of the 34-year modeling period. 20 °C (68 °F) was analyzed as this is the temperature likely to decrease rainbow trout and native Grand Canyon fishes survival based on life histories of both fish. The Enhanced Coordination Alternative met the preferred minimum performance for fish (that is, not exceeding 20 °C [68 °F] in one or more days out of the 34-year modeling period) in 71 percent of simulated futures. The Enhanced Coordination Alternative had the greatest number of simulated futures that maintained cooler water temperatures at Lees Ferry, which is beneficial for rainbow trout and limits smallmouth bass reproduction, but these temperatures also inhibit native fish growth and reproduction. Alternatives with larger simulated river flows and higher Lake Powell elevations generally maintained cooler water temperatures in more simulated futures than alternatives with lower simulated river flows and Lake Powell elevations. However, during extended droughts, every alternative had a greater number of simulated futures with undesirable temperature increases, affecting fish habitat and species composition. See **TA 8.2.3** and **TA 8.2.5**, **TA 8**, Biological Resources – Fish and Other Aquatic Species, for more detailed information on changes in water temperature from Glen Canyon Dam downstream through the Grand Canyon to Pearce Ferry and impacts on sportfish, native Grand Canyon fishes, and nonnative predatory fish.

TA 14.2.2, **TA 14**, Recreation, describes the impact of temperature on recreation, particularly impacts on sportfish populations. Water temperatures exceeding 20 °C (68 °F) can cause thermal stress and mortality of rainbow trout while creating conditions more favorable for the growth of nonnative fish and smallmouth bass. Additionally, warmer water temperatures may increase the competitive advantage for brown trout, as this species is more tolerant of elevated temperatures. Over the full modeling period, the Enhanced Coordination Alternative had the greatest number of simulated futures that maintained cooler water temperatures at Lees Ferry, which is beneficial for sportfish, like rainbow trout, and limits smallmouth bass reproduction. See **TA 14.2.2**, **TA 14**, Recreation, for more detailed information on temperature impacts on recreation associated with sportfish populations.

Analysis key takeaways:

- At Lees Ferry under Wet and Moderately Wet Flow Categories, all alternatives had similar simulated median temperatures. However, in the Average Flow Category, Enhanced Coordination and Maximum Operational Flexibility Alternatives had lower median simulated annual average and maximum daily temperatures, with a narrower interquartile range, compared with other alternatives at both Lees Ferry and Pearce Ferry.

- Under Dry and Critically Dry Flow Categories, simulated median values for annual average of daily temperatures and maximum temperatures for both Lees Ferry and Pearce Ferry increased across alternatives compared with the Wet and Moderately Wet Flow Categories, and the Enhanced Coordination Alternative had the lowest median values for simulated annual average of daily temperatures and maximum temperatures. Additionally, the interquartile ranges increased across all alternatives, indicating more variability in annual average of daily temperatures and maximum temperatures as flow conditions become drier. The CCS Comparative Baseline had the highest annual maximum median temperature among all alternatives.
- The Enhanced Coordination Alternative had the greatest number of simulated futures that maintained cooler water temperatures at both Lees Ferry and Pearce Ferry, which is beneficial for rainbow trout and limits smallmouth bass reproduction, but these temperatures also inhibit native fish growth and reproduction.

TA 6.2.4 Issue 3: How would reservoir storage, reservoir releases, and corresponding changes in river flows downstream of the reservoirs affect dissolved oxygen?

Dissolved oxygen dynamics can be affected by reservoir drawdowns through several pathways, including remobilization of deposited sediment as water levels change. Lower reservoir elevations may result in plumes of low dissolved oxygen from resuspended sediment at the penstock elevation. Thus, the effects of reservoir storage will likely vary based on inflow conditions, with an increased potential for greater variability between annual minimum and maximum concentrations (Deemer et al. 2025). As older reservoirs like Lake Powell experience lower elevations, there is greater metaliminion dissolved oxygen consumption, with larger spring snowmelt inflows furthering dissolved oxygen declines (Deemer et al. 2025). Dissolved oxygen is also affected by certain operations. For example, as reservoir levels decrease below 3,490 feet at Lake Powell, use of the river outlet works is triggered, which leads to high dissolved oxygen concentrations downstream of the Glen Canyon Dam due to aeration as water passes through the river outlet works (Vernieu 2010).

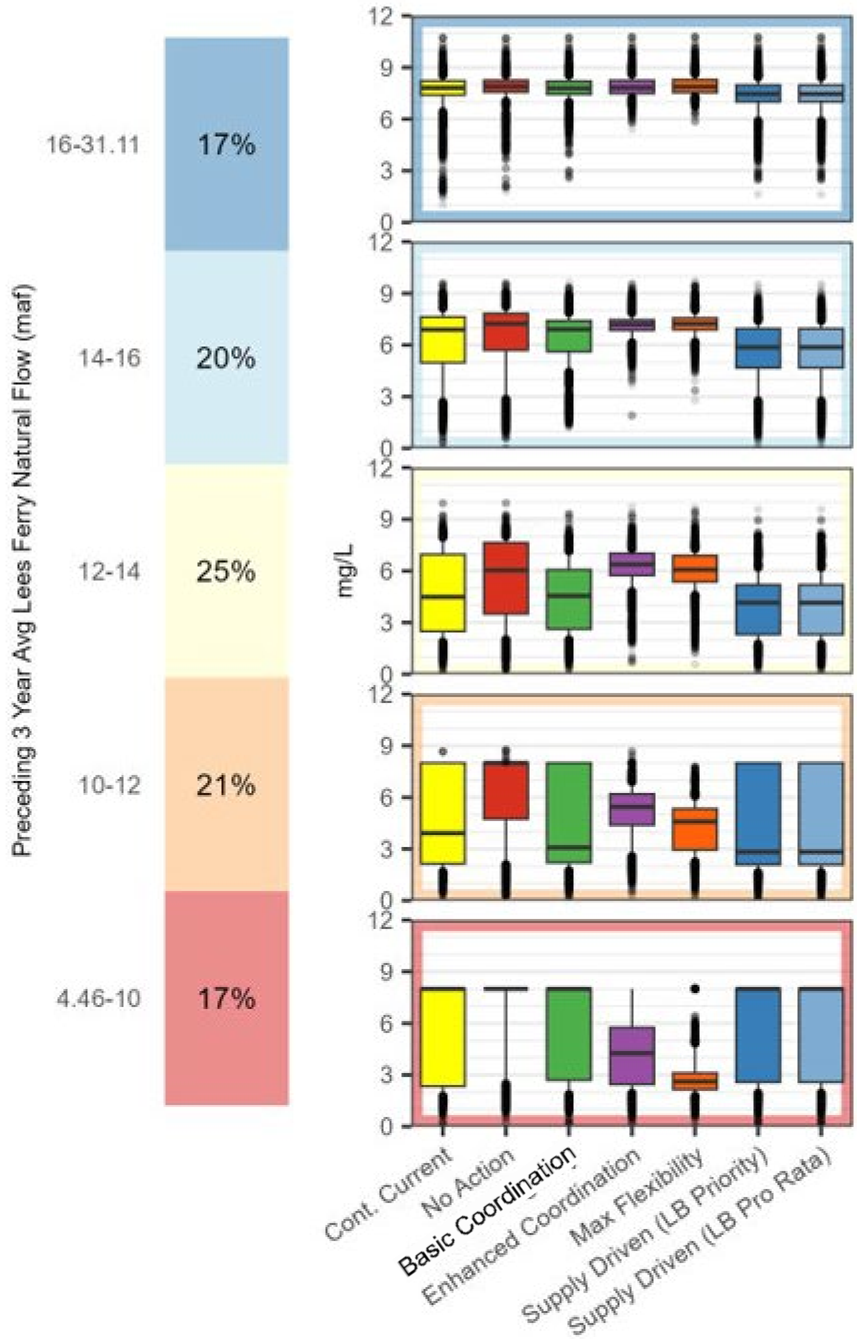
Figure TA 6-11 displays the response of minimum annual dissolved oxygen concentrations released from Glen Canyon Dam to different hydrologic conditions under the alternatives by looking at the preceding 3-year average of Lees Ferry natural flows. In the Average Flow Category (12–14 maf), the medians and interquartile ranges for minimum annual dissolved oxygen concentrations fall between 7 to 8 mg/L. As flow categories got drier, the median values decreased across alternatives, and variability increased across alternatives.

Analysis of minimum annual dissolved oxygen concentrations under various hydrologic scenarios shows that, in wetter years (the Wet Flow Category, 16-31.11 maf), median dissolved oxygen levels are similar across all alternatives, generally falling between 7 and 8 mg/L (see **Figure TA 6-11**). However, in drier flow categories, both the median dissolved oxygen and the variability across alternatives decrease, with greater differences emerging among the alternatives. The Enhanced Coordination and Maximum Operational Flexibility Alternatives generally result in higher minimum annual dissolved oxygen concentrations under drier conditions, making them more robust against low dissolved oxygen and reservoir elevations during extended droughts.

Figure TA 6-12 displays a robustness analysis where the minimum annual dissolved oxygen concentration of Glen Canyon Dam releases is greater than different values in at least 90 percent of years. The row with the minimum dissolved oxygen concentrations greater than 2 mg/L is highlighted, as this is considered hypoxia in most streams and rivers (Blaszczak et al. 2023). Under these assumptions, the Enhanced Coordination and Maximum Operational Flexibility Alternatives have the greatest percentage of futures under which simulated minimum dissolved oxygen concentrations are greater than 2 mg/L in at least 90 percent of years for the full modeling period. The simulated minimum dissolved oxygen concentrations are greater than 2 mg/L in the fewest number of futures under the CCS Comparative Baseline, and the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) across the full modeling period.

When Lake Powell's elevation drops below 3,490 feet, dam operations will use the river outlet works to pass water through the dam. To capture this change to dam operations and aeration of water through the river outlet works, the Grand Canyon Monitoring and Research Center Dissolved Oxygen Model (Deemer et al. 2025) uses 8 mg/L as a conservative minimum. This 8 mg/L assumption can be seen in **Figure TA 6-11** and **Figure TA 6-12** under the Critically Dry Flow Category (4.46-10 maf), where reservoir elevations fall below 3,490 feet under the No Action, Basic Coordination, Supply Driven (both LB Priority and LB Pro Rata approach) Alternatives, and the CCS Comparative Baseline. While dissolved oxygen would increase because releases from the river outlet works would effectively aerate Glen Canyon Dam releases, this assumption does not capture the operational constraints of using the river outlet works over extended periods of use. Further, as described in **Chapter 2**, Reclamation maintains the authority to modify operations to protect Glen Canyon Dam infrastructure. Therefore, due to the limitation of long-term use of the river outlet works, a minimum annual dissolved oxygen concentration greater than 2 mg/L and elevations below 3,490 feet at Lake Powell were considered, as shown in **Figure TA 6-13**. Under these assumptions, the Enhanced Coordination and Maximum Operational Flexibility Alternatives are the only alternatives under which simulated minimum dissolved oxygen concentrations are greater than 2 mg/L in at least 90 percent of years in a majority of futures (greater than 50 percent) for the full modeling period. Similar to analyzing minimum dissolved oxygen concentrations alone, the simulated minimum dissolved oxygen concentrations are greater than 2 mg/L and elevations below 3,490 feet at Lake Powell in the fewest number of futures under the CCS Comparative Baseline, and the Supply Driven Alternative (both LB Priority and LB Pro Rate approaches) across the full modeling period.

Figure TA 6-11
Minimum Annual Dissolved Oxygen Concentration Released from Glen Canyon Dam*



*8 mg/L is used as a conservative minimum when Lake Powell's elevation drops below 3,490 feet and dam operations use the river outlet works to pass water through the dam (Deemer et al. 2025). Under the Basic Coordination and Supply Driven (both LB Priority and LB Pro Rata approach) Alternatives, and the CCS Comparative Baseline, the median, upper quartile, and maximum values are 8 mg/L in the Critically Dry Flow Category (4.46-10 maf); therefore, the upper quartile is collapsed to a single point that is the same value as the median. Under the No Action Alternative, the maximum, the upper quartile, median, and lower quartile values are 8 mg/L in the Critically Dry Flow Category (4.46–10 maf); therefore, the box is collapsed to a single point and represented as a single horizontal line.

Figure TA 6-12
Dissolved Oxygen Concentration in Glen Canyon Dam Releases: Robustness. Percent of futures in which the minimum annual dissolved oxygen concentration is greater than the value specified in each row in at least 90 percent of years

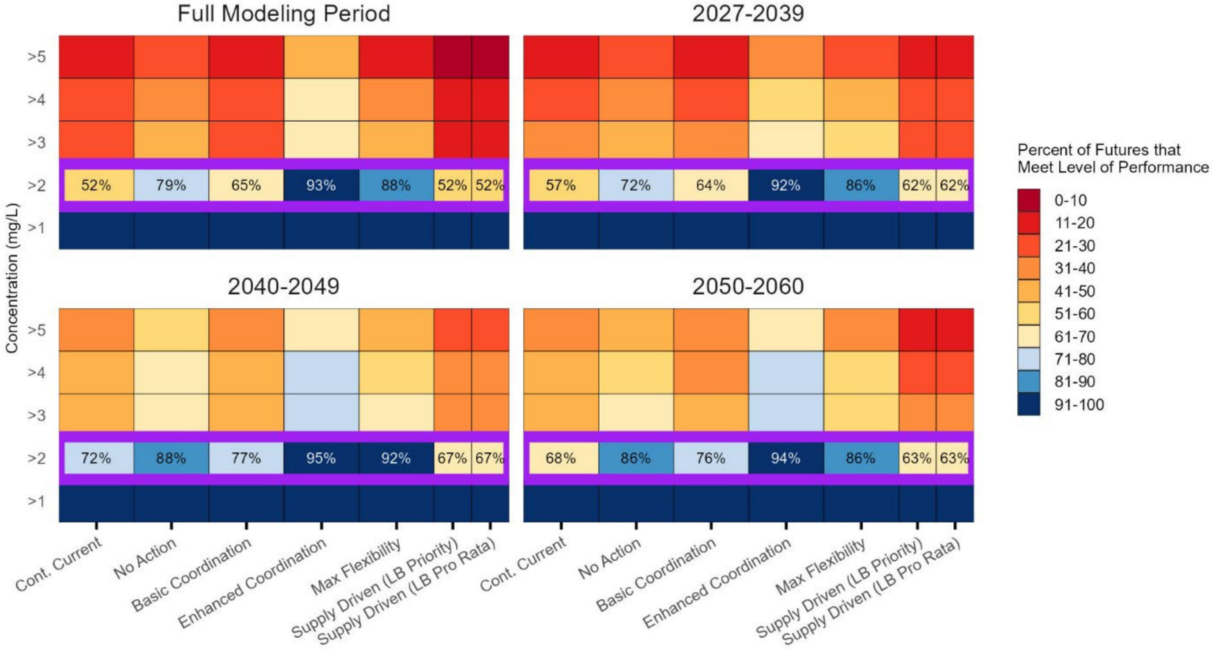


Figure TA 6-13
Lake Powell 3,490 and Dissolved Oxygen Concentration: Robustness. Percent of futures in which Lake Powell elevation stays above 3,490 feet and the minimum annual dissolved oxygen concentration is greater than the value specified in each row in at least 90 percent of years

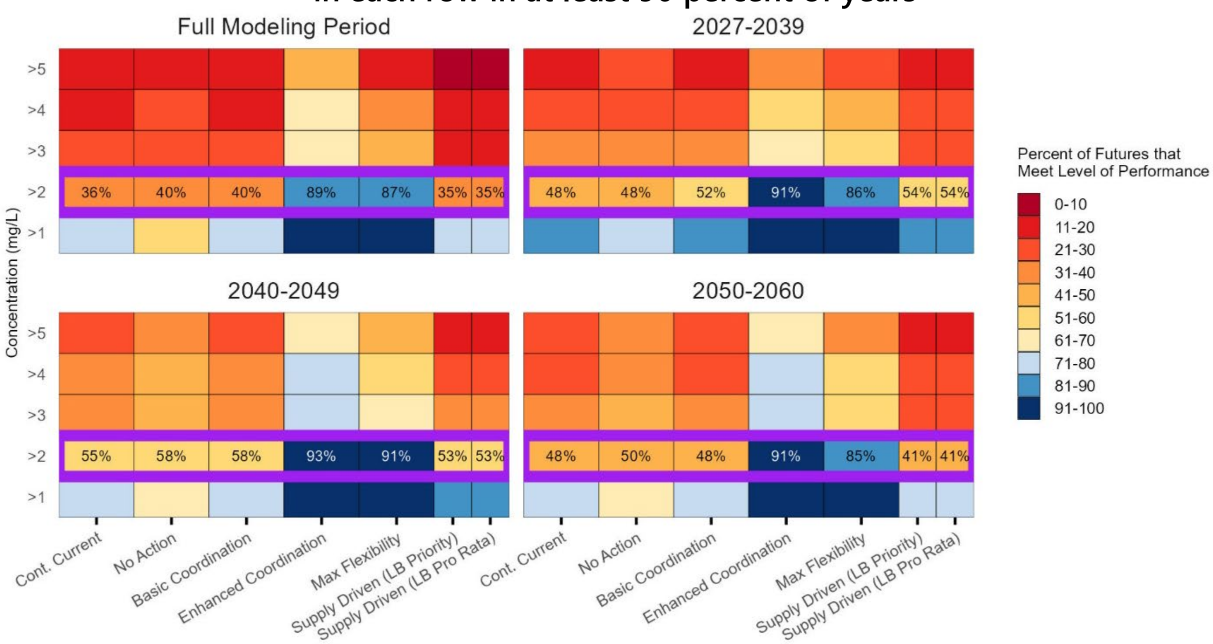
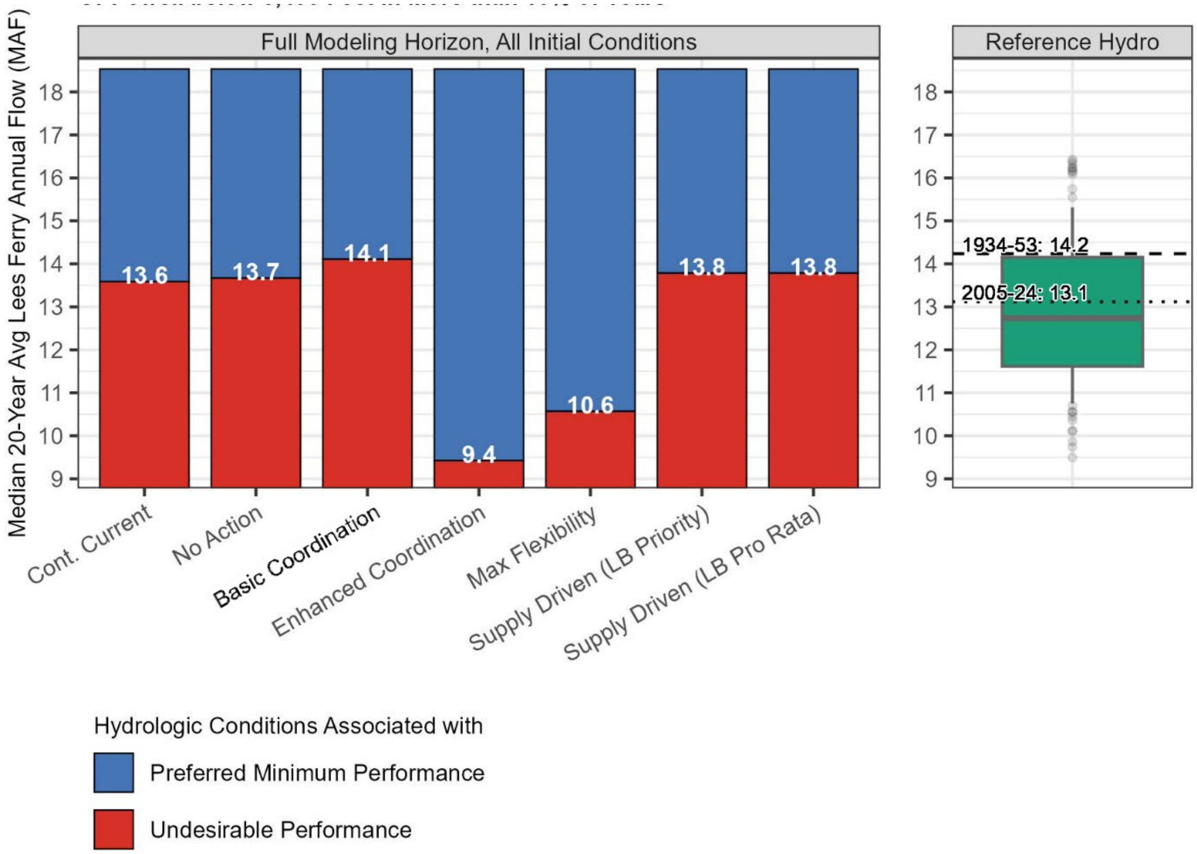


Figure TA 6-14 presents the vulnerability analysis for simulated minimum annual dissolved oxygen concentrations released from Glen Canyon Dam, with the reference hydrology on the right of the vulnerability bar plot. Due to the limitation of long-term use of the river outlet works, vulnerability was only analyzed for conditions that could cause dissolved oxygen concentration less than 2 mg/L or Lake Powell elevation below 3,490 feet in more than 10 percent of years. The median 20-year average of Lees Ferry annual flows in the reference hydrology is shown on the right side of the vulnerability bar plot. The reference hydrology's median value is 12.7 maf, and the most recent 20-year average Lees Ferry annual flow (13.1 maf from 2005–2024) is represented by a dotted line for comparison. In the reference hydrology panel, the historical median 20-year average Lees Ferry annual flow is 14.2 maf from 1934–1953, which is represented by a dashed line.

Figure TA 6-14
Lake Powell 3,490 and Dissolved Oxygen Concentration: Vulnerability. Conditions that Could Cause Dissolved Oxygen Concentration Less than 2 mg/L or Powell below 3,490 Feet in More than 10 percent of Years.



As shown on **Figure TA 6-14**, under the CCS Comparative Baseline and the No Action, Basic Coordination, and Supply Driven (both LB Priority and LB Pro Rata approaches) Alternatives, the hydrologic conditions associated with undesirable performance (dissolved oxygen concentrations from Glen Canyon Dam releases falling below 2 mg/L or Lake Powell elevations below 3,490 feet) are greater than the median hydrology in the reference ensemble and that of the most recent driest 10-year average Lees Ferry annual flow (13.1 maf from 2005–2024). Therefore, the hydrologic conditions associated with undesirable performance for the CCS Comparative Baseline and the No Action, Basic Coordination, and Supply Driven (both LB Priority and LB Pro Rata approaches) Alternatives fall within a majority of hydrologic conditions that have already been observed.

Figure TA 6-14 also shows that the Enhanced Coordination and Maximum Operational Flexibility Alternatives result in undesirable performance (dissolved oxygen concentrations from Glen Canyon Dam releases falling below 2 mg/L or Lake Powell elevations below 3,490 feet) at 20-year average Lees Ferry flows below 9.4 maf and 10.6 maf, respectively. Flows associated with these hydrologic conditions are lower than the lowest 25 percent of hydrologic conditions that have already been observed (11.6 maf).

TA 8.2.3, **TA 8**, Biological Resources – Fish and Other Aquatic Resources, describes dissolved oxygen impacts on fish. The section also presents dissolved oxygen concentration thresholds of less than 3 mg/L, which can lead to reduced survival and feeding efficiencies, and of 6–9 mg/L, which are optimal for growth and survival at all life stages. Analysis of simulated minimum annual dissolved oxygen concentrations under various hydrologic scenarios shows that, in the Wet Flow Category (16–31.11 maf), the median dissolved levels are similar across all alternatives, generally falling between 7 and 8 mg/L (see **Figure TA 6-11**). However, as shown on **Figure TA 6-13**, under the Critically Dry Flow Category (4.46–10 maf), Lake Powell elevations stay above 3,490 feet and the simulated minimum annual dissolved oxygen concentration is greater than 3 mg/L in at least 90 percent of the years in a majority of futures under the Enhanced Coordination Alternative; this occurs under the other alternatives is less than 50 percent of futures, which is critical for survival and feeding efficiencies of fish. See **TA 8.2.3**, **TA 8**, Biological Resources – Fish and Other Aquatic Resources, for more information on the impact of dissolved oxygen on fish.

Analysis key takeaways:

- Under the Wet Flow Category, the alternatives had similar simulated median dissolved oxygen at Lees Ferry. Under drier conditions, the Enhanced Coordination and Maximum Operational Flexibility Alternatives generally had higher simulated minimum annual dissolved oxygen concentrations than the other alternatives when considering futures in which Lake Powell elevations stay above 3,490 feet.
- By controlling for elevation at Lake Powell below 3,490 feet, the effect of bypass tube releases on dissolved oxygen concentrations is not captured, the Enhanced Coordination and Maximum Operational Flexibility Alternatives are the only alternatives under which simulated minimum dissolved oxygen concentrations are greater than 2 mg/L in a majority of futures (greater than 50 percent) for the full modeling period. The simulated minimum dissolved oxygen concentrations are greater than 2 mg/L in the fewest number of futures

under the CCS Comparative Baseline and the Supply Driven (both LB Priority and LB Pro Rata approaches) Alternatives across the full modeling period.

- The Enhanced Coordination and Maximum Operational Flexibility Alternatives result in undesirable performance (dissolved oxygen concentrations from Glen Canyon Dam releases falling below 2 mg/L or Lake Powell elevations below 3,490 feet), below the lowest 25 percent of hydrologic conditions already observed. The hydrologic conditions associated with undesirable performance for the CCS Comparative Baseline and the No Action, Basic Coordination, and Supply Driven (both LB Priority and LB Pro Rata approaches) Alternatives fall within a majority of hydrologic conditions that have already been observed.
- Under the Critically Dry Flow Category (4.46–10 maf), Lake Powell elevations stay above 3,490 feet and the simulated minimum annual dissolved oxygen concentration is greater than 3 mg/L in at least 90 percent of the years in a majority of futures under the Enhanced Coordination Alternative; this occurs under the other alternatives in less than 50 percent of futures, which is critical for survival and feeding efficiencies of fish. See **TA 8.2.3**, **TA 8**, Biological Resources – Fish and Other Aquatic Resources, for more information on the effect of dissolved oxygen on fish.

TA 6.2.5 Issue 4: How would reservoir storage, reservoir releases, and corresponding changes in river flows downstream of the reservoirs affect harmful algal blooms and nutrients?

Cyanobacteria blooms can alter physical and chemical water quality properties, threaten aquatic species, and release toxins into water bodies, leading to health effects for recreationists and affecting water supplies. As reservoir water levels decline, the risk of cyanobacterial blooms in reservoirs increases with more severe water level fluctuations and/or declines (Hoffman et al. 2025). However, examples also exist of no marked water quality responses to long-term water level drawdown, including Lake Mead. For example, Lake Mead reservoir has experienced dramatic multiyear reductions in water level with no apparent effects on nutrient or chlorophyll a concentrations (Hannoun and Tietjen 2022). Additionally, contrary to the hypothesis that cyanobacteria would have increased throughout the reservoir, phytoplankton communicated structure remains largely stable, except for shallow areas where increases in temperature or phosphorus levels were observed (van der Nagel et al. 2025)

In **TA 3 Hydrologic Resources**, **Figure TA 3-6** shows that the water year (WY) minimum values for each alternative are similar in wetter hydrology. However, in the Average Flow Category (12–14 maf), the Maximum Operational Flexibility and Enhanced Coordination Alternatives exhibit less variability and greater median WY minimum than the other alternatives.

Additionally, **Figure TA 3-6**, Water Year Minimum and End of Water Year Elevations and Storage Volumes of Lake Powell, in **TA 3**, Hydrologic Resources, indicates that in the Critically Dry Flow Category (4.46–10 maf), the median WY minimum Lake Powell elevations are lowest amongst the CCS Comparative Baseline and the No Action, Basic Coordination, and Supply Driven (both LB Priority and LB Pro Rata approaches) Alternatives. The median WY minimum Lake Powell elevations are highest in the Enhanced Coordination and Maximum Operational Flexibility Alternatives. The Enhanced Coordination Alternative is the only alternative under which the median

WY minimum Lake Powell elevation is above the 3,500 feet threshold. Based on the latest literature review on the impact of lake levels on cyanobacteria and these simulated WY minimums, the CCS Comparative Baseline, and the No Action, Basic Coordination, and Supply Driven (both LB Priority and LB Pro Rata approaches) Alternatives would have an increased risk for cyanobacterial blooms associated with declining reservoir elevations.

In considering severe water level fluctuations as a marker of increased risk for cyanobacterial blooms in reservoirs, **Figure TA 9-7**, Robustness Heat Map showing Lake Powell maximum Annual Surface Elevation Variability in any 10-year Period, in **TA 9**, Vegetation Including Special Status Species, shows that the Enhanced Coordination Alternative had the greatest number of simulated futures in which the maximum annual change in water surface elevation is less than 30.71 feet in 5 years or more out of 10 years during the full modeling period compared with the other alternatives. Less severe water level fluctuations are associated with a lower risk of cyanobacterial blooms, which could indicate a decreased risk under the Enhanced Coordination Alternative compared with the other alternatives.

Key analysis takeaways:

- The CCS Comparative Baseline, and the No Action, Basic Coordination, and Supply Driven (both LB Priority and LB Pro Rata approaches) Alternatives would pose an increased risk of cyanobacterial blooms due to the lower simulated Lake Powell elevations. These increased risks would be greatest under the Critically Dry Flow Category (4.46–10 maf) associated with lower reservoir elevations.
- The Enhanced Coordination Alternative had the greatest number of simulated futures in which the maximum annual change in water surface elevation was less than 30.71 feet in 5 years or more out of 10 years during the full modeling period. This could decrease the risk of cyanobacterial blooms associated with severe water level fluctuations under the Enhanced Coordination Alternative compared with the other alternatives.

TA 6.2.6 Issue 5: How would reservoir storage and reservoir releases affect reservoir dilution capacity?

Generally, as reservoir elevations decrease, the dilution capacity of reservoirs like Lake Powell and Lake Mead would also decrease. Decreased dilution capacity from lower reservoir elevations could result in greater concentrations of pollutants of concern, such as PFAS. Therefore, the impacts of reservoir elevations on pollutants, such as PFAS, could be greater in the alternatives with the lowest median WY minimum reservoir elevations (see **Figure TA 3-6**, End of Water Year and Water Year Minimum Elevation and Storage Volumes of Lake Powell, in **TA 3**, Hydrologic Resources), including the CCS Comparative Baseline, and the No Action, Basic Coordination, and Supply Driven (both LB Priority and LB Pro Rata approaches) Alternatives. Quantifiable water quality impacts related to dilution capacity are not available at the time of this environmental impact statement. However, it is unlikely that any of the reservoir elevations of the alternatives would substantially reduce the dilution capacity and increase the concentration of pollutants of concern.

Key Analysis Takeaways:

- Given the current data and modeling capabilities, the impacts of the alternatives on pollutants of concern could not be quantitatively assessed. The impact of decreased dilution capacity associated with lower reservoir elevations on pollutants of concern, such as PFAS, would be greatest under alternatives with the lowest median WY minimum reservoir elevations, including the CCS Comparative Baseline, and the No Action, Basic Coordination, and Supply Driven (both LB Priority and LB Pro Rata approaches) Alternatives. However, this impact would likely be negligible since it is unlikely that any of the reservoir elevations in the alternatives would significantly reduce dilution capacity or increase the concentration of pollutants of concern.

TA 6.2.7 Summary Comparison of Alternatives

Under the Average Flow Category (12–14 maf), the maximum simulated annual flow-weighted salinity concentrations under the CCS Comparative Baseline and the No Action and Basic Coordination Alternatives exceeded the salinity threshold below Hoover Dam. Simulated annual flow-weighted salinity concentrations were greatest under the Critically Dry Flow Category (4.46–10 maf) under all alternatives due to the lowest reservoir elevations associated with these hydrologic conditions. Under the Critically Dry Flow Category, simulated average flow-weighted average salinity concentration upper extremes exceeded the salinity thresholds at all sites under all alternatives. Under all alternatives, a majority (90 percent or greater) of simulated futures did not exceed the salinity criteria in even the most challenging hydrologic conditions.

Considering the robustness of simulated salinity results, compared with the other alternatives, simulated futures under the No Action Alternative exceeded the salinity threshold below Hoover Dam under the greatest percentage of futures over the full modeling period. However, under all alternatives, a majority of simulated futures **did not exceed** the salinity criteria established by the Colorado River Basin Salinity Control Forum below Hoover Dam, below Parker Dam, or at Imperial Dam. Salinity for releases below Parker Dam and at Imperial Dam were highly correlated with releases below Hoover Dam.

In a vulnerability analysis of conditions that could cause salinity concentrations below Hoover Dam to exceed 723 mg/L, the hydrologic conditions associated with undesirable performance for the No Action Alternative (9.8 maf) **are less than the median of previously** observed hydrology in the reference ensemble. The hydrologic conditions associated with undesirable performance for the Basic Coordination, Enhanced Coordination, and Maximum Operational Flexibility Alternatives are less than the 25th percentile of previously observed hydrology in the reference ensemble. Further, the hydrologic conditions associated with undesirable performance for the Supply Driven Alternatives (both LB Priority and LB Pro Rata approaches) (6.8 maf) are less than any previously observed conditions in the reference hydrology (7.8 maf).

All alternatives had similar simulated annual average of daily temperatures and maximum temperatures at Lees Ferry and Pearce Ferry under Wet and Moderately Wet Flow Categories, but in the Average Flow Category, simulated annual average of daily temperatures and maximum temperatures under the Enhanced Coordination and Maximum Operational Flexibility Alternatives had a lower interquartile and overall range than the other alternatives. Under Dry and Critically Dry Flow Categories, simulated median annual average of daily temperatures and maximum temperatures and interquartile ranges increased across all alternatives, but the Enhanced Coordination Alternative had the lowest simulated median annual average of daily temperatures and maximum temperatures. CCS Comparative Baseline had the greatest annual maximum median temperature compared with the alternatives, which indicates that continuing current operations would have the potential to lead to the greatest maximum median temperature compared with all other alternatives.

The Enhanced Coordination Alternative had the greatest number of simulated futures that maintained cooler water temperatures at Lees Ferry and Pearce Ferry, which is beneficial for rainbow trout and limits smallmouth bass reproduction, but these temperatures also inhibit native fish growth and reproduction. See **TA 8.2.3**, **TA 8**, Biological Resources – Fish and Other Aquatic Resources, and **TA 14.2.2**, **TA 14**, Recreation, for more detailed information on changes in water temperature from Glen Canyon Dam downstream through the Grand Canyon to Pearce Ferry and impacts on rainbow trout and other sport fish, native Grand Canyon fishes, and nonnative predatory fish.

The CCS Comparative Baseline and the No Action, Basic Coordination, Supply Driven (both LB Priority and LB Pro Rata approaches) Alternatives would pose an increased risk of cyanobacterial blooms due to the lower simulated Lake Powell elevations. These increased risks are more exaggerated under the Critically Dry Flow Category associated with lower reservoir elevations. The Enhanced Coordination Alternative had the greatest number of simulated futures in which the maximum annual change in water surface elevation was less than 30.71 feet in 5 years or more out of 10 years during the full modeling period. This could decrease the risk for cyanobacterial blooms associated with severe water level fluctuations under the Enhanced Coordination Alternative compared with the other alternatives.

Overall, the Enhanced Coordination and Maximum Operational Flexibility Alternatives have the best performance for dissolved oxygen under median 20-year average Lees Ferry annual flow and better relative maximum and average Colorado River temperature at Lees Ferry compared with the other alternatives. These alternatives also had slightly higher flows associated with hydrologic conditions associated with undesirable performance compared with the Supply Driven (both LB Priority and LB Pro Rata approaches) Alternatives; however, undesirable performance for the Enhanced Coordination and Maximum Operational Flexibility Alternatives was still lower than 25 percent of hydrologic conditions that have already been observed.

TA 6.3 Glossary

Dissolved oxygen – The measure of how much oxygen is dissolved in water; this is also the amount of oxygen that is available to living aquatic organisms.

Epilimnion – The uppermost, warm water layer in lakes and reservoirs, which is separate from the deeper, more-dense, colder water layer (hypolimnion).

Hypolimnion – The bottom, colder, denser layer in lakes and reservoirs, which is separate from the upper, less dense, warmer layer (epilimnion).

Oligotrophic – Waterbodies or habitats with low concentrations of nutrients.

Salinity – The dissolved salt content of a body of water and a strong contributor to conductivity.

Stratification – The separation of a body of water into distinct and stable vertical layers based on the density of water. Differences in water density results in differences in temperature and/or salinity.

Total dissolved solids – The combined content of all substances in a liquid volume. Total dissolved solids are related to salinity, which is the total concentration of all dissolved salts in water. The sum of constituents is defined to include calcium, magnesium, sodium, chloride, sulfate, a measure of the carbonate equivalent of alkalinity and, if measured, silica and potassium. Salinity and total dissolved solids are often used interchangeably in Colorado River salinity discussions.

TA 6.4 References

Arizona Department of Environmental Quality (AZDEQ). 2022. Feasibility Study Lake Havasu Avenue and Holly Avenue Water Quality Assurance Revolving Fund Site Lake Havasu City, Arizona. Internet website: https://static.azdeq.gov/wqarf/havasu_holly_fs22.pdf.

_____. 2024. Community update: Soil Removal Action Complete as Groundwater Cleanup Continues at the Pacific Gas & Electric Company Topock Compressor Station. Internet website: https://static.azdeq.gov/vrp/sites/dtsc_update.pdf.

Blaszczak, J. R., L. E. Koenig, F. H. Mejia, L. Gomez-Gener, C. L. Dutton, A. M. Carter, N. B. Grimm, J. W. Harvey, A. M. Helton, and M. J. Cohen. 2023. "Extent, patterns, and drivers of hypoxia in the world's streams and rivers." *Limnology and Oceanography Letters* 8 (453-463). doi: 10.1002/lol2.10297.

Brooks, P. D., D. K. Solomon, S. Kampf, S. Warix, C. Bern, D. Barnard, H. R. Barnard, G. T. Carling, R. W. H. Carroll, J. Chorover, A. Harpold, K. Lohse, F. Meza, J. McIntosh, B. Neilson, M. Sears, and M. Wolf. 2025. Groundwater dominates snowmelt runoff and controls streamflow efficiency in the western United States. Communication earth & environment. Internet website: https://www.nature.com/articles/s43247-025-02303-3.

Bureau of Reclamation (Reclamation). 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/.

_____. 2022. Colorado River Basin Salinity Control Program. Internet website: https://www.usbr.gov/uc/progact/salinity/.

California Water Boards. 2022. Status of Actions October 2022: PG&E Hinkley Chromium Contamination. Internet website: https://www.waterboards.ca.gov/rwqcb6/water_issues/projects/pge/docs/2022/PGE-Status-of-Actions-October-2022.pdf.

Colorado River Basin Salinity Control Forum. 2023. 2023 Review, Water Quality Standards for Salinity, Colorado River System. October 2023. Internet website: https://www.coloradoriversalinity.org/docs/2023%20Review%20(final%20with%20appendices%20to%20print).pdf.

Deemer, B. R., C. M. Andrews, K. E. Strock, N. Voichick, J. Hensleigh, J. R. Beaver, and R. Radtke. 2023. Over half a century record of limnology data from Lake Powell, desert southwest United States: From reservoir filling to present day (1964–2021). *Limnology and Oceanography Letters* 8(4): 580–94. Internet website: https://doi.org/10.1002/lol2.10310.

Deemer, B. R., C. M. Andrews, R. H. Reibold, B. A. Mihalevich, T. A. Sabol, J. Drewel, and C. B. Yackulic. 2025. Low water levels interact with reservoir aging to increase the severity of summertime metalimnion dissolved oxygen minima in Lake Powell, desert Southwest, USA. Inland Water, 15(1). Internet website: https://doi.org/10.1080/20442041.2025.2476309.

Deemer, B. R., D. E. Eppehimer, C. B. Yackulic. 2026. Modeled dissolved oxygen and water temperature in the Colorado River in Grand Canyon in support of resource impact analysis for Post-2026 reservoir operational alternatives: U.S. Geological Survey data release. Internet website: https://doi.org/10.5066/P1R3BM7Z.

Deemer, B. R., E. G. Stets, and C. B. Yackulic. 2020. Calcite precipitation in Lake Powell reduces alkalinity and total salt loading to the Lower Colorado River Basin. Internet website: https://aslopubs.onlinelibrary.wiley.com/doi/full/10.1002/lno.11399.

Dibble, D. L., C. B. Yackulic, T. A. Kennedy, K. R. Bestgen, and J. C. Schmidt. 2021. "Water storage decisions will determine the distribution and persistence of imperiled river fishes." *Ecological Applications* 31(2): e02279. Internet website: https://doi.org/10.1002/eap.2279.

Eppehimer, D. E., C. B. Yackulic, L. A. Bruckerhoff, J. Wang, K. L. Young, K. R. Bestgen, B. A. Mihalevich, and J. C. Schmidt. 2025. Declining reservoir elevations following a two-decade drought increase water temperatures and non-native fish passage facilitating a downstream invasion. *Canadian Journal of Fisheries and Aquatic Sciences* 82:1–19.

Grand Canyon Monitoring and Research Center (GCMRC). 2025. Discharge, Sediment and Water Quality, Grand Canyon Stations, Colorado River at Lees Ferry, AZ. Internet website: https://www.gcmrc.gov/discharge_qw_sediment/station/GCDAMP/09380000#.

Hannoun, D., J. Belding, T. Tietjen, and R. Devaney. 2021. Assessing treatability with simulated lake drawdown: Quantifying drought-driven turbidity in source water. *AWWA Water Science* e1295. Internet website: https://awwa.onlinelibrary.wiley.com/doi/pdf/10.1002/aws2.1295.

Hannoun, D., Tietjen, T., and K. Brooks. 2022. The Influence and Implications of Climate Change on Water Quality in a Large Water Reservoir in the Southwest, USA. American Journal of Climate Change, 2022, 11, 197-229. Internet website: scirp.org/pdf/ajcc_2022092714554566.pdf.

Hannoun, D. and T. Tietjen. 2022. "Lake Management under severe drought: Lake Mead, Nevada/Arizona." *Journal of the American Water Resources Association* 59(2): 416–28. Internet website: https://doi.org/10.1111/1752-1688.13090.

Havens, K. 2012. Effects of Climate Change on the Eutrophication of Lakes and Estuaries. IFAS Extension University of Florida. Internet website: https://www.cakex.org/sites/default/files/documents/SG12700.pdf.

Hoffman, K. K., B. R. Deemer, M. E. Lofton, N. D. Gibney, and C. C. Carey. 2025. Assessing risk for enhanced cyanobacteria, phytoplankton, and pathogens with changes in water level regime with potential application to Lake Powell and Lake Mead: A mixed methods literature review. Science Report NPS/SR —2025/226. National Park Service, Fort Collins, Colorado. Internet website: https://doi.org/10.36967/2307521.

Mihalevich, B. A., B. T. Neilson, C. A. Buahin, C. B. Yackulic, and J. C. Schmidt. 2020. "Water temperature controls for regulated canyon-bound rivers." *Water Resources Research* 56(12). Internet website: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020WR027566.

Miller, O.L., Putman, A.L., Smith, R.A., Schwarz, G.E., Hess, M.D., McDonnell, M.C., and D.K. Jones. 2024. Temporal Variability in Irrigated Land and Climate Influences on Salinity Loading across the Upper Colorado River Basin, 1986-2017. Environmental Research Letters. Internet website: https://doi.org/10.1088/1748-9326/ad18dd.

Moody, C. D. and D. K. Mueller. 1984 Water Quality of the Colorado River System: Historical Trends in Concentration, Load, and Mass Fraction of Inorganic Solutes. Internet website: https://www.usbr.gov/tsc/techreferences/rec/REC-ERC-84-9.pdf.

National Park Service (NPS). 2025. Water Advisory for Lake Powell. News release data: July 2, 2025. Internet website: https://www.nps.gov/glca/learn/news/20250702.htm.

Richards, R.J., 2025, Salinity Loads at 20-stations in the Colorado River Basin: U.S. Geological Survey data release, Internet website: https://doi.org/10.5066/P14N44JU.

Rumsey, C. A., Miller, M. P., Schwarz, G., Hirsch, R. M., & Susong, D. D. 2017. The role of baseflow in dissolved solids delivery to streams in the Upper Colorado River Basin. *Hydrological Processes*, 31, 4705-4718. Internet website: https://doi.org/10.1002/hyp.11390

Rumsey, C.A., Miller, O., Hirsch, R.M., Marston, T.M., and D.D. Susong. 2021. Substantial Declines in Salinity Observed Across the Upper Colorado River Basin During the 20th Century, 1929–2019. *Water Resources Research*, 57, e2020WR028581. Internet website: https://doi.org/10.1029/2020WR028581.

Saari, G.N., Z. Wang, and B. W. Brooks. 2018. Revisiting inland hypoxia: diverse exceedances of dissolved oxygen thresholds for freshwater aquatic life. *Environmental Science and Pollution Research* 25, 3139–3150 (2018) Internet website: http://link.springer.com/10.1007/s11356-017-8908-6.

Southern Nevada Water Authority (SNWA). 2023. EIS data for Lake Mead and Lake Mohave.

Thompson, K.A., Ray, H., Gerrity, D., Quinones, O., Dano, E., Prieur, J., Vanderford, B., Steinle-Darling, E., and E.R.V. Dickenson. n.d. Sources of Per- and Polyfluoroalkyl Substances in an Arid, Urban, Wastewater-Dominated Watershed. Pre-print.

United States Environmental Protection Agency (EPA). 1986. Ambient water quality criteria for dissolved oxygen. Office of Research and Development, Environmental Research Laboratories, Duluth, Minnesota. Internet website: https://www.epa.gov/sites/default/files/2019-03/documents/ambient-wqc-dissolved-oxygen-1986.pdf.

_____. 2014. Cyanobacteria and Cyanotoxins: Information for Drinking Water Systems. Internet website: https://www.epa.gov/sites/default/files/2014-08/documents/cyanobacteria_factsheet.pdf.

_____. 2017. Gold King Mine Monitoring Data November 2016-June 2017. Internet website: https://www.epa.gov/sites/default/files/2018-01/gkm_nov2016-june2017_follow-up_data_final.xlsx.

United States Geological Survey (USGS). 2012. A Synthesis of Aquatic Science for Management of Lakes Mead and Mohave. Internet website: https://pubs.usgs.gov/circ/1381/pdf/circ1381.pdf#page=62.

_____. 2018. Gold King Mine release (2015): USGS water-quality data and activities. Water Resources Mission Area. Internet website: https://www.usgs.gov/mission-areas/water-resources/science/gold-king-mine-release-2015-usgs-water-quality-data-and.

_____. 2019. Nutrients and Eutrophication. Water Resources Mission Area. Internet website: https://www.usgs.gov/mission-areas/water-resources/science/nutrients-and-eutrophication.

_____. 2021. Large Decreases in Upper Colorado River Salinity Since 1929: Long-term Data to Help Protect Water Quality for US and Mexico. Internet website: https://www.usgs.gov/news/state-news-release/large-decreases-upper-colorado-river-salinity-1929.

van der Nagel, C., D. Hannoun, and T. Tietjen. 2025. Stable phytoplankton community compositions in Lake Mead (Nevada-Arizona, USA) during two decades of severe drought. *Environmental Science and Ecotechnology,* Volume 23, 2025, 100491, ISSN 2666-4984. Internet website: https://www.sciencedirect.com/science/article/pii/S2666498424001054?via%3Dihub.

Vernieu, W. S. 2010. Effects of the 2008 High-Flow Experiment on Water Quality in Lake Powell and Glen Canyon Dam Releases, Utah-Arizona. Internet website: https://pubs.usgs.gov/of/2010/1159/.

Walters, D. M., E. Rosi-Marshall, T. A. Kennedy, W. F. Cross, and C. V. Baxter. 2015. "Mercury and selenium accumulation in the Colorado River food web, Grand Canyon, USA." *Environmental Toxicology and Chemistry* 34(10): 2385–94.

Wang, H., Q. Li, and J. Xu. 2023. Climate Warming Does Not Override Eutrophication, but Facilitates Nutrient Release from Sediment and Motivates Eutrophic Process. Microorganisms. Internet website: https://pmc.ncbi.nlm.nih.gov/articles/PMC10143447/#:~:text=Under%20eutrophic%20conditions%2C%20elevated%20temperature,rates%20%5B20%2C23%5D.

Zohary, T., I. Ostrovsky. 2011. Ecological impacts of excessive water level fluctuations in stratified freshwater lakes. *Inland Waters*, *1*(1), 47–59. Internet website: https://www.tandfonline.com/doi/abs/10.5268/IW-1.1.406.