Technical Appendix 12

Paleontological Resources

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Acronyms and Abbreviations

Acronym or Abbreviation	Full Phrase
2007 Final EIS	2007 Interim Guidelines Final Environmental Impact Statement
BLM	Bureau of Land Management
CCS	Continued Current Strategies
cfs	cubic feet per second
Department	United States Department of the Interior
DMDU	Decision Making under Deep Uncertainty
GCMRC	Grand Canyon Monitoring and Research Center
HFE	high-flow experiment
LB Priority	Lower Basin Priority
LB Pro Rata	Lower Basin Pro Rata
LTEMP	Long-Term Experimental and Management Plan
maf	million acre-feet
NPS	National Park Service
NRA	National Recreation Area
PFYC	Potential Fossil Yield Classification
PRPA	Paleontological Resources Preservation Act
Reclamation	Bureau of Reclamation
SIB	Southerly International Boundary
U.S.	United States
USGS	United States Geological Survey

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TA 12. Paleontological Resources

TA 12.1 Affected Environment

Paleontological resources include any fossilized remains, traces, or imprints of organisms preserved in rock. The Paleontological Resources Preservation Act of 2009 (PRPA; 16 United States [U.S.] Code 470aaa–470aaa-11) and its implementation rule (43 Code of Federal Regulations 49) require that U.S. Department of the Interior (Department) agencies preserve, manage, and protect paleontological resources on lands administered by the Bureau of Reclamation (Reclamation), the National Park Service (NPS), the Bureau of Land Management (BLM), and the U.S. Fish and Wildlife Service. The PRPA ensures these federally owned resources are available for current and future generations to enjoy and study as part of America's national heritage.

The Colorado River Basin, a region renowned for its rich biodiversity and invaluable paleontological resources, faces a range of significant challenges stemming from fluctuating water levels, climate trends, and increasing human demands. As one of the most heavily managed rivers in the U.S., its waters are primarily allocated for agricultural, urban, and hydropower needs. However, this management, while crucial for sustaining these sectors, inadvertently impacts the delicate ecosystems that rely on the river's flow. Beyond the biological consequences, the fluctuating water levels also affect the paleontological sites embedded within the riverbanks and surrounding landscapes. Fossils, trackways, and other paleontological remains, often hidden beneath layers of sediment, are increasingly exposed as water levels fluctuate, leaving them vulnerable to erosion, weathering, and human disturbances. Fossils are nonrenewable resources and once degraded or destroyed can result in the permanent loss of important scientific information about life and environments in the earth's past. Proper management actions can identify how to reduce impacts on paleontological resources, leading to their preservation and enhancing our knowledge of earth and life through time.

The NPS is primarily responsible for conservation of natural and cultural resources and the visitor experience, including recreation, at both Lake Mead and Lake Powell. Reclamation manages water operations. Both agencies comply with the PRPA.

The Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead Final Environmental Impact Statement (2007 Final EIS; Reclamation 2007) and the 2024 Glen Canyon Dam Long-Term Experimental Management Plan (LTEMP) Final Supplemental Environmental Impact Statement (Reclamation 2024a) do not address paleontological resources as a separate resource concern; the Near-term Colorado River Operations Final Supplemental Environmental Impact Statement does (Reclamation 2024b). In the 2007 and 2024 analyses, many potential impact issues related to reservoir levels and changes in river flows are analogous to those for cultural resources, such as paleontological resources.

TA 12.1.1 Study Area

The study area for paleontological resources stretches from the northern extent of Lake Powell to the Southerly International Boundary (SIB) in California. It covers approximately 1 million acres across Utah, Arizona, Nevada, and California. The study area encompasses the Colorado River channel from bank to bank, extending from the canyon rim to canyon rim in areas from Glen Canyon Dam to Lake Mead through the Grand Canyon. A 0.5-mile buffer is applied to the full-pool volume of Lake Powell and Lake Mead. The same buffer is applied to the lower Colorado River corridor from Hoover Dam to the SIB. This includes the known and unknown resources in Lake Powell and Lake Mead. It is important to note that the resources within fluctuating water levels are vulnerable to wave action; those above are at risk from visitation impacts.

This region of the southwestern U.S. contains a rich paleontological record, with fossils and traces of marine and terrestrial life preserved in the sedimentary strata, dating back over 1.2 billion years (Santucci and Tweet 2021). However, much of these resources have been submerged by the creation of the reservoirs at Lake Powell and Lake Mead, with minimal data available on the deepwater zones, which are less vulnerable to disturbance. In contrast, the operational zones and areas above fluctuating water levels, which have been partially inventoried, are at greater risk from erosion, wave action, and human activity. Erosion, accelerated by land and water management along the Colorado River, exposes fossils more quickly, providing opportunities for discovery but also increasing the risk of loss. As water levels fluctuate, previously submerged fossils are exposed to environmental threats like wind, sun, and temperature fluctuations, causing weathering and degradation.

The PRPA requires federal protection, but the ongoing exposure of these resources highlights the need for more effective preservation efforts. The PRPA also requires Department agencies to develop plans to inventory and monitor using scientific principles and expertise. These plans should emphasize interagency coordination and collaborative efforts, when possible.

Paleontological Resources Assessment Criteria

In recognizing that paleontological resources are considered to include not only fossil remains and traces but also the fossil-collecting localities and the geologic units containing those fossils and localities, the BLM developed a procedure for evaluating the paleontological resource potential of individual geologic units. This procedure uses the Potential Fossil Yield Classification (PFYC) system to assign ranks to geologic units based on the relative abundance of vertebrate fossils or scientifically significant invertebrate or plant fossils and the sensitivity of these fossils to adverse impacts (BLM 2007, 2016). Under the PFYC system, geologic units with a higher potential are assigned a higher classification number. The PFYC system, as defined by the BLM, is used by other Department agencies (BLM-IM-2016-124) and is outlined as follows:

PFYC Class 5—Very High

This class includes highly fossiliferous geologic units that consistently and predictably produce significant paleontological resources. Units assigned to Class 5 have some or all of the following characteristics:

- Significant paleontological resources have been documented and occur consistently.
- Paleontological resources are highly susceptible to adverse impacts from surface-disturbing activities.
- The unit is frequently the focus of illegal collecting activities.

PFYC Class 4—High

This class includes geologic units that are known to contain a high occurrence of paleontological resources. Units assigned to Class 4 typically have the following characteristics:

- Significant paleontological resources have been documented but may vary in occurrence and predictability.
- Surface-disturbing activities may adversely affect paleontological resources.
- Rare or uncommon fossils, including nonvertebrate (such as soft body preservation) or unusual plant fossils, may be present.
- Illegal collecting activities may impact some areas.

PFYC Class 3—Moderate

This class includes sedimentary geologic units where fossil content varies in significance, abundance, and predictable occurrence. Units assigned to Class 3 have some of the following characteristics:

- They are marine in origin with sporadic known occurrences of paleontological resources.
- Paleontological resources may occur intermittently, but abundance is known to be low.
- Units may contain significant paleontological resources, but these occurrences are widely scattered.
- The potential for an authorized land use to impact a significant paleontological resource is known to be low to moderate.

PFYC Class 2—Low

This class includes geologic units that are not likely to contain paleontological resources. Units assigned to Class 2 typically have one or more of the following characteristics:

- Field surveys have verified that significant paleontological resources are not present or are very rare.
- Units are generally younger than 10,000 years before present.
- There are recent aeolian deposits.
- Sediments exhibit significant physical and chemical changes (that is, diagenetic alteration) that make fossil preservation unlikely.

PFYC Class 1—Very Low

This class includes geologic units that are not likely to contain recognizable paleontological resources. Units assigned to Class 1 typically have one or more of the following characteristics.

- The geologic units are igneous or metamorphic, excluding air-fall and reworked volcanic ash units.
- The geologic units are Precambrian (for example, Proterozoic) in age.

PFYC Class U—Unknown

This class includes geologic units that cannot receive an informed PFYC assignment. Characteristics of Class U may include the following:

- The geologic units may exhibit features or preservation conditions that suggest significant paleontological resources could be present, but little information about the actual paleontological resources of the unit or area is known.
- The geologic units represented on a map are based on lithologic character or basis of origin, but they have not been studied in detail.
- Scientific literature does not exist or does not reveal the nature of paleontological resources.
- Reports of paleontological resources are anecdotal or have not been verified.
- The area or geologic unit is poorly studied or understudied.
- BLM staff has not yet been able to assess the nature of the geologic unit.

PFYC Class W—Water

This class includes any surface area that is mapped as water. Most bodies of water do not normally contain paleontological resources. However, shorelines should be carefully considered for uncovered or transported paleontological resources. Reservoirs are a special concern because important paleontological resources are often exposed during low water intervals. In karst areas, sinkholes and cenotes may trap animals and contain paleontological resources. Dredging river systems may result in the disturbance of sediments that contain paleontological resources.

Deep Time and the Geologic Time Scale

Earth's history extends back more than 4.6 billion years and reflects a long and complex sequence of physical and biological events. To organize this vast span of time, geologists developed the geologic time scale, which serves as an international framework for describing the earth's past. The time scale divides geologic history into formally named intervals—such as eras, periods, and epochs—based on rock sequences that preserve evidence of past environments, geologic events, and life forms.

Similar to how a calendar divides a year into months, weeks, and days, the geologic time scale uses a hierarchy of time units that allows scientists to describe events at different levels of detail. The names of these intervals were often derived from geographic regions where representative rock formations were first studied.

When the time scale was first developed in the 18th and 19th centuries, it was based on relative dating, recognizing that in an undisturbed sequence of rock layers, the lower layers are older than those above. With the discovery of radioactivity in the late 19th century, scientists gained the ability to determine absolute ages of rocks by measuring the decay of radioactive isotopes. This advancement made it possible to assign numerical ages to geologic time intervals and better understand the timing of major geologic and biological events.

Figure TA 12-1, below, depicts the geologic time scale put together by the NPS, and includes the geologic time divisions discussed in the text and included in the PFYC geodatabase. **Figure TA 12-2** is a more in-depth depiction of the time scale.

Table TA 12-1 summarizes the number of acres by PFYC value in the study area. **Map TA 12-1** through **Map TA 12-8** depict PFYC values in the study area. These PFYC maps were created by first compiling a composite geologic map of the study area and then assigning PFYC rankings to each geologic rock unit.

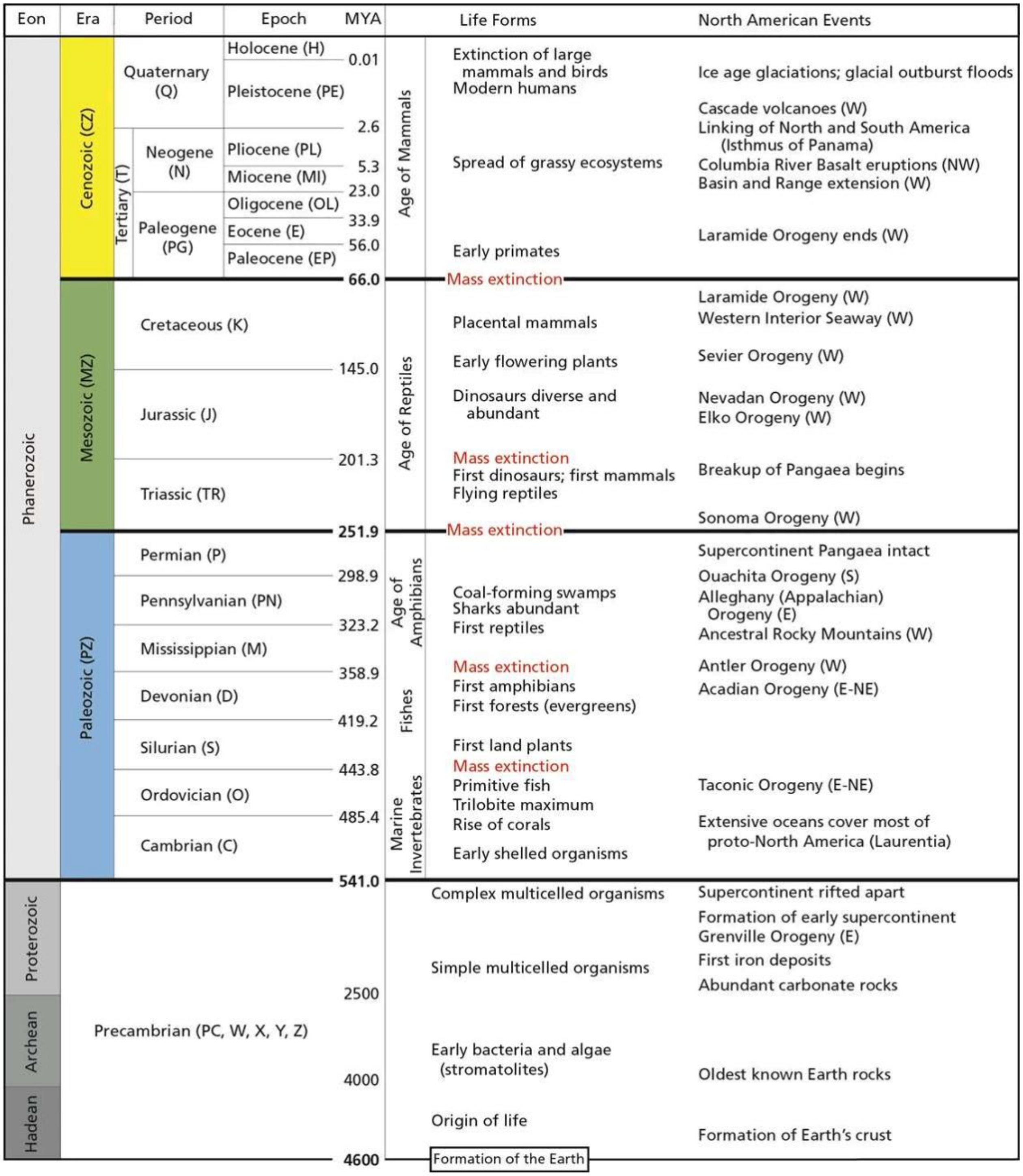
Table TA 12-1
Acres of PFYC within the Study Area

PFYC	Total Acres
1	70,500
2	154,600
3	103,600
4	179,300
5	24,200
U	113,700
W	373,100
Total acres	**1,019,000**

Source: BLM GIS 2025
Note: PFYC data do not cover the entire study area, especially in the waterbodies and portions of the Colorado River.

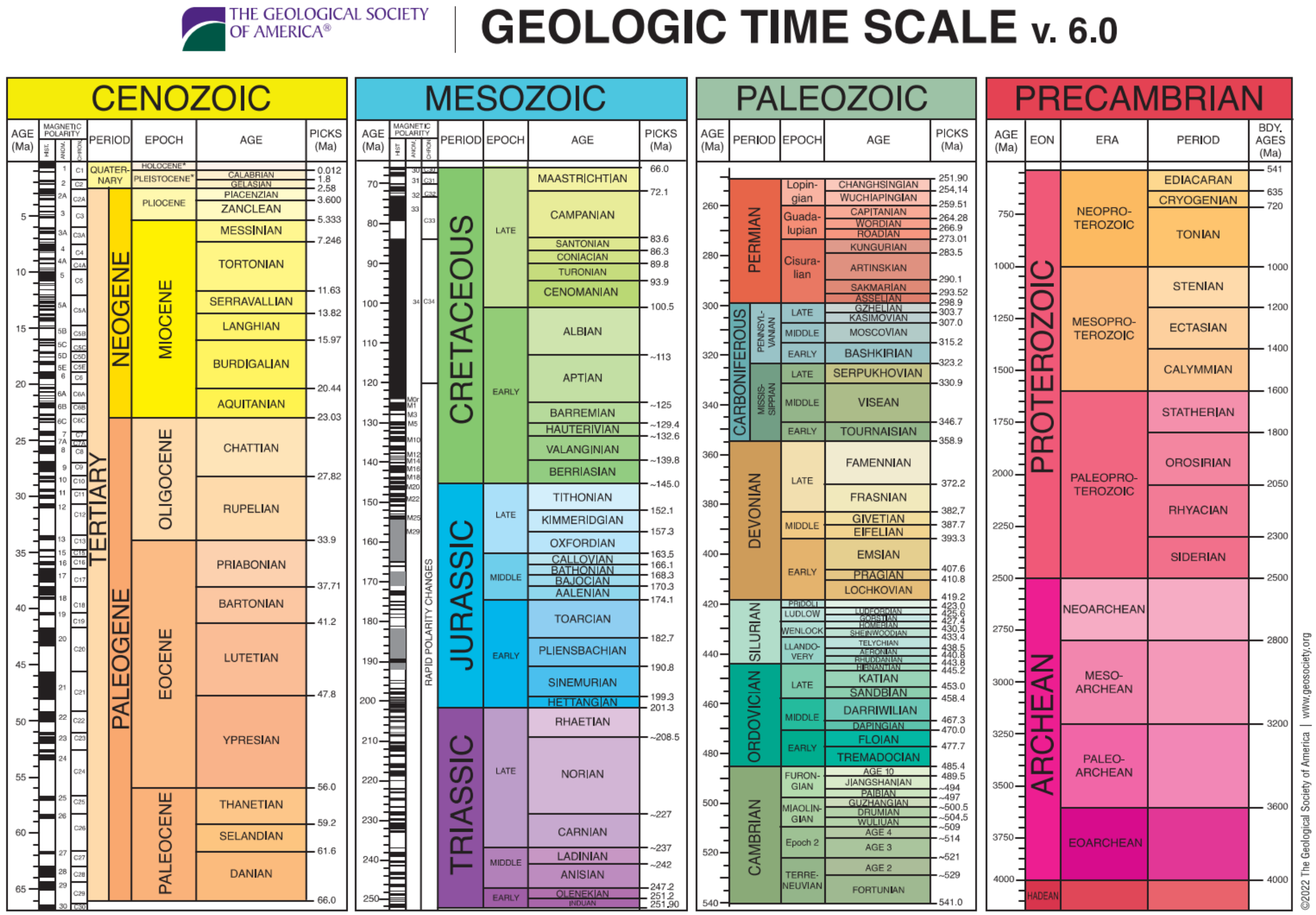
Formation-by-formation summaries of resource type, distribution, and PFYC system classes for all geologic units in the study area are in **Table TA 12-2**.

Figure TA 12-1
Simplified Geologic Time Scale



Source: NPS 2018

Figure TA 12-2
Geologic Time Scale



*The Pleistocene is divided into four ages, but only two are shown here. What is shown as Calabrian is actually three ages: Calabrian from 1.8 to 0.774 Ma, Chibanian from 0.774 to 0.129 Ma, and Late from 0.129 to 0.0117 Ma. The Holocene is divided into three ages: Greenlandian from 0.0117 to 0.0082 Ma, Northgrippian from 0.0082 to 0.0042 Ma, and Meghalayan from 0.0042 to present. The geologic community broadly recognizes the Anthropocene as a proposed new time interval of Earth history, partly coincident with the Holocene. Currently, the Anthropocene has an informal designation, with a proposed age span extending from the present to a beginning point between ca. 15,000 yr B.P. and as recent as 1960 CE.

The Cenozoic, Mesozoic, and Paleozoic are the Eras of the Phanerozoic Eon. Names of units and age boundaries usually follow the Gradstein et al. (2012), Cohen et al. (2012), and Cohen et al. (2013, updated) compilations. Numerical age estimates and picks of boundaries usually follow the Cohen et al. (2013, updated) compilation. The numbered epochs and ages of the Cambrian are provisional. A "~" before a numerical age estimate typically indicates an associated error of ± 0.4 to more than 1.6 Ma.

Walker, J.D., and Geissman, J.W., compilers, 2022, Geologic Time Scale v. 6.0: Geological Society of America, https://doi.org/10.1130/2022.CTS006C. (Walker—University of Kansas; Geissman—University of Texas–Dallas, University of New Mexico.)

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Cohen, K.M., Finney, S., and Gibbard, P.L., 2012, International Chronostratigraphic Chart: International Commission on Stratigraphy, https://stratigraphy.org/ICSchart/ChronostratChart2012.pdf (accessed Sept. 2022).
Cohen, K.M., Finney, S.C., Gibbard, P.L., and Fan, J.-X., 2013 (updated), The ICS International Chronostratigraphic Chart: Episodes, v. 36, p. 199–204, http://www.stratigraphy.org/ICSchart/ChronostratChart2021-10.pdf (accessed Sept. 2022).
Gradstein, F.M, Ogg, J.G., Schmitz, M.D., et al., 2012, The Geologic Time Scale 2012: Boston, USA, Elsevier, https://doi.org/10.1016/B978-0-444-59425-9.00004-4.

Source: GSA 2022

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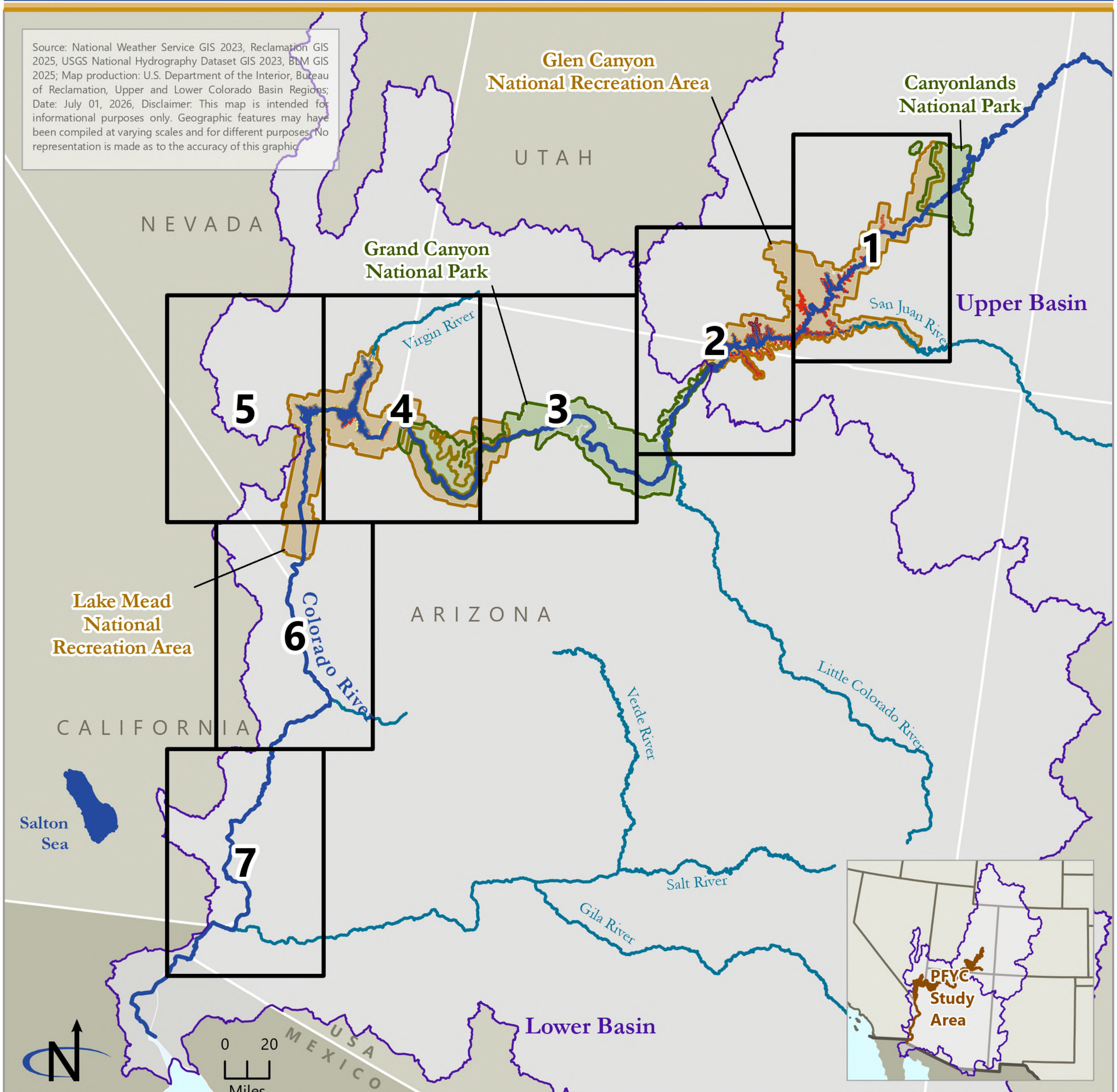
RECLAMATION

Map TA 12-1
Potential Fossil Yield Classification—Overview



Class 5—Very high	Map extent
Class 4—High	Colorado River
Class 3—Moderate	Major Colorado River tributary
Class 2—Low	National park
Class 1—Very low	National recreation area
Class U—Unknown	Colorado River Basin, Upper and Lower Basins
Class W—Water	States in the Colorado River Basin (Wyoming, Colorado, Utah, and New Mexico are Upper Division states, and Arizona, California, and Nevada are Lower Division states)

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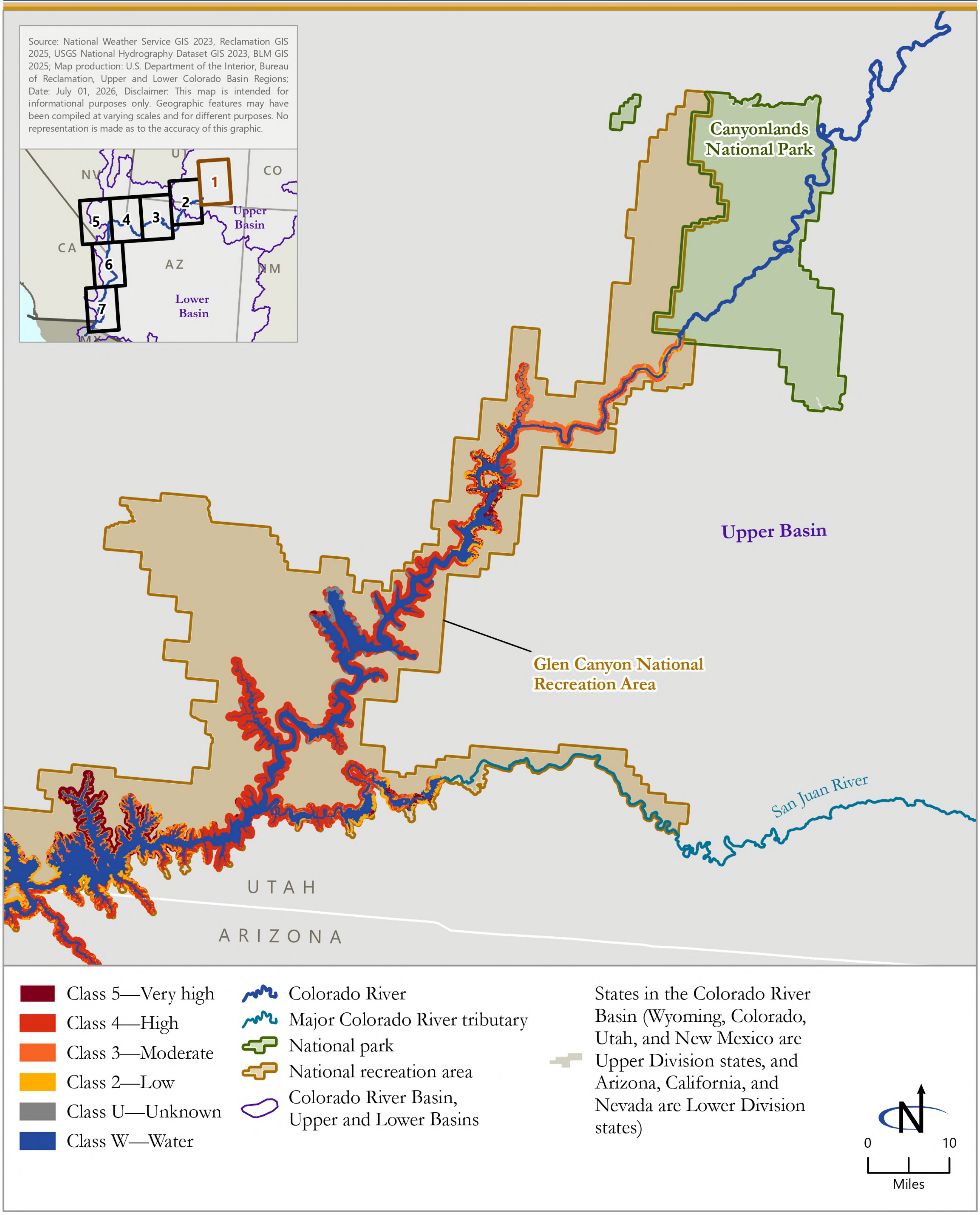
RECLAMATION

Map TA 12-2
Potential Fossil Yield Classification—Extent 1



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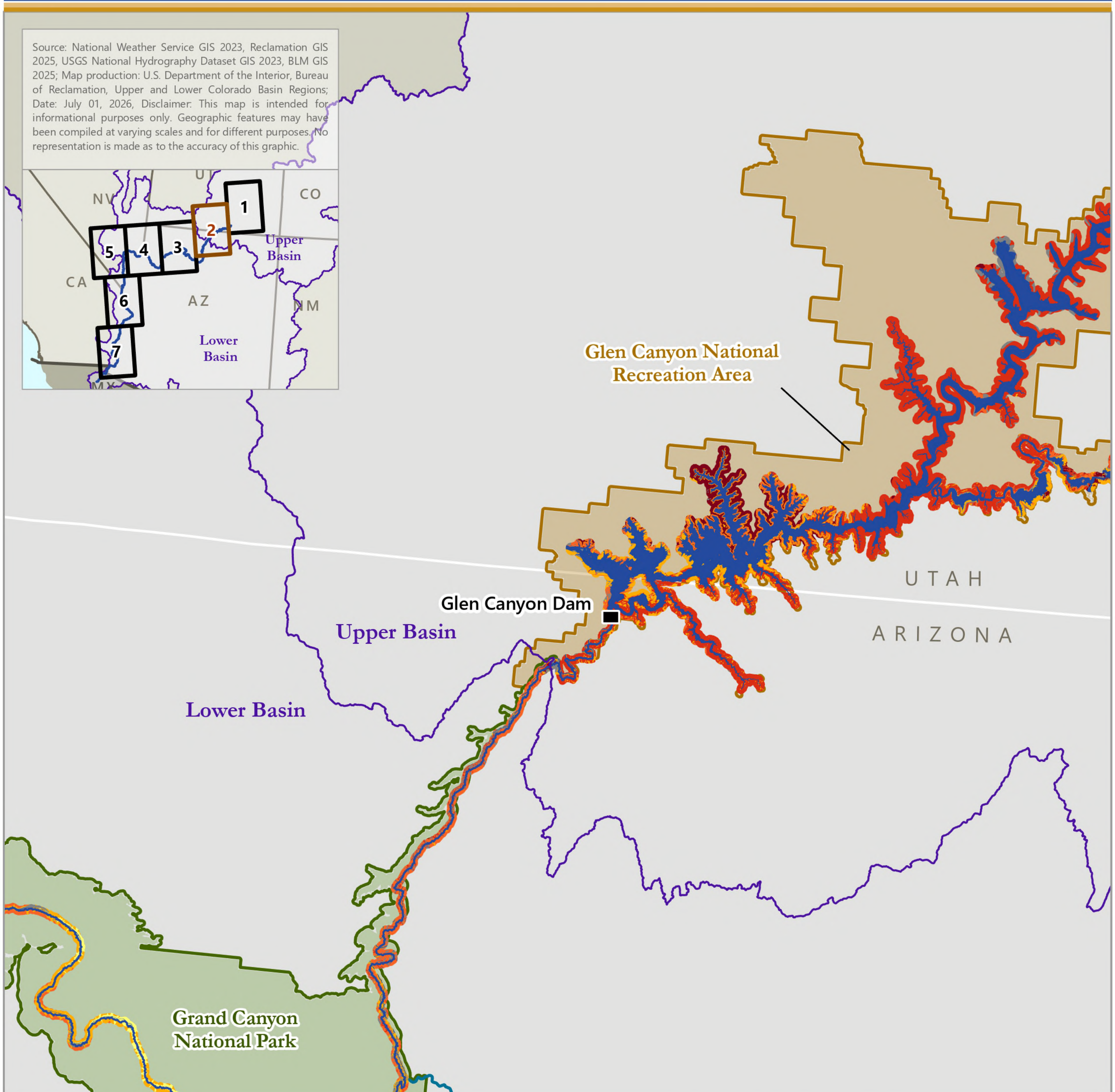
Map TA 12-3
Potential Fossil Yield Classification—Extent 2



Class 5—Very high
Class 4—High
Class 3—Moderate
Class 2—Low
Class 1—Very low
Class U—Unknown
Class W—Water

Major dam
Colorado River
Major Colorado River tributary
National park
National recreation area
Colorado River Basin, Upper and Lower Basins

States in the Colorado River Basin (Wyoming, Colorado, Utah, and New Mexico are Upper Division states, and Arizona, California, and Nevada are Lower Division states)

N
0 10
Miles

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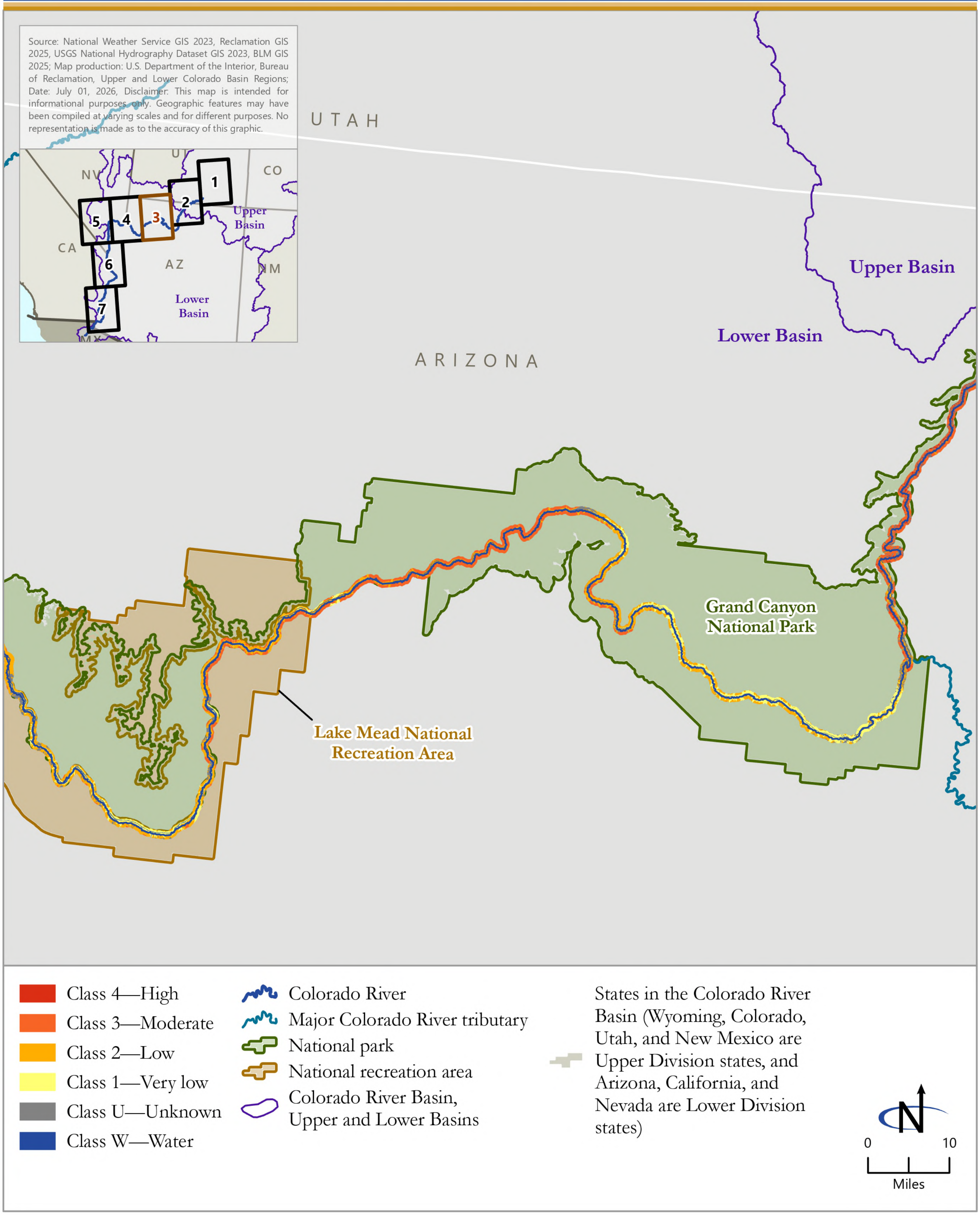
Map TA 12-4
Potential Fossil Yield Classification—Extent 3



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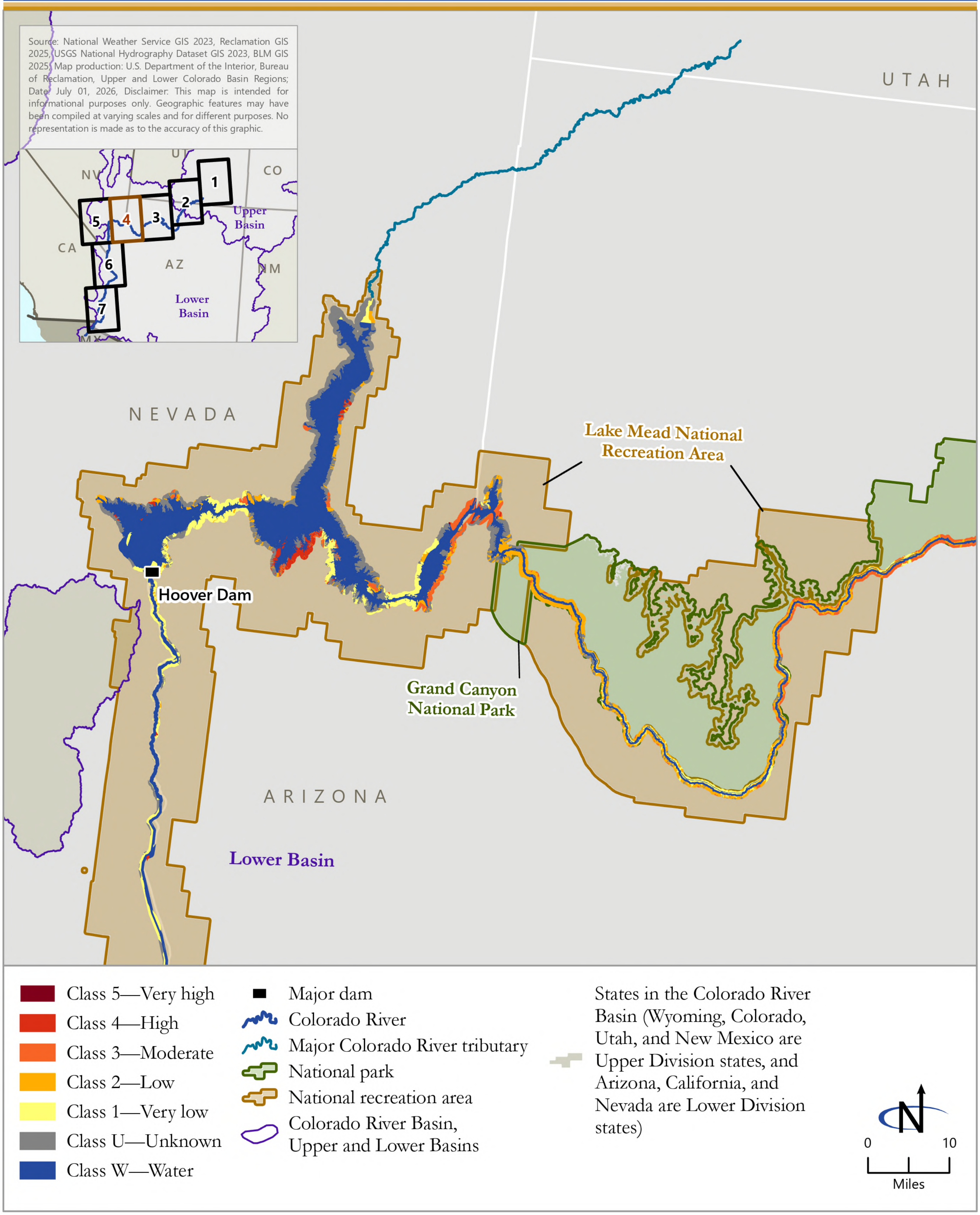
Map TA 12-5
Potential Fossil Yield Classification—Extent 4



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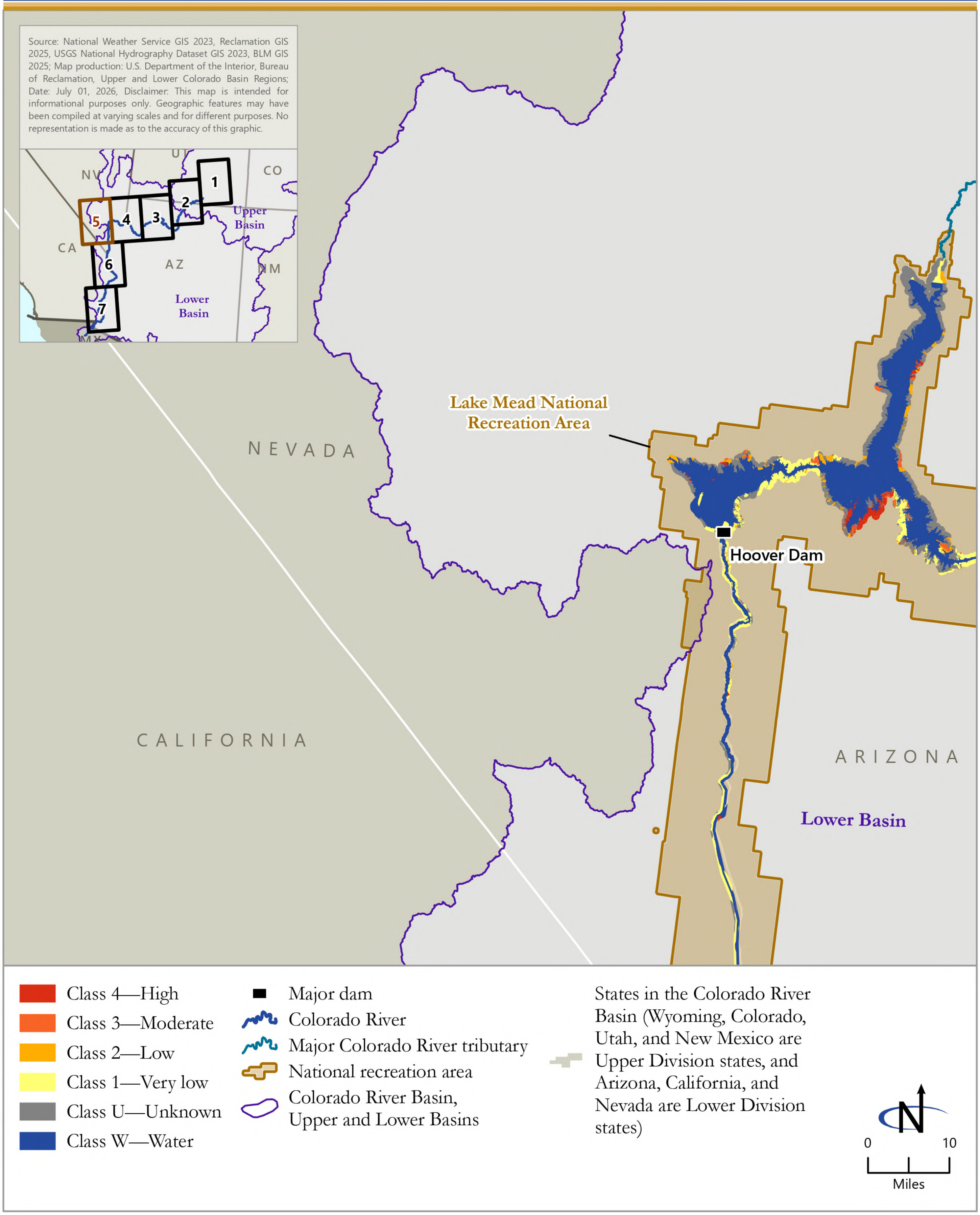
Map TA 12-6
Potential Fossil Yield Classification—Extent 5



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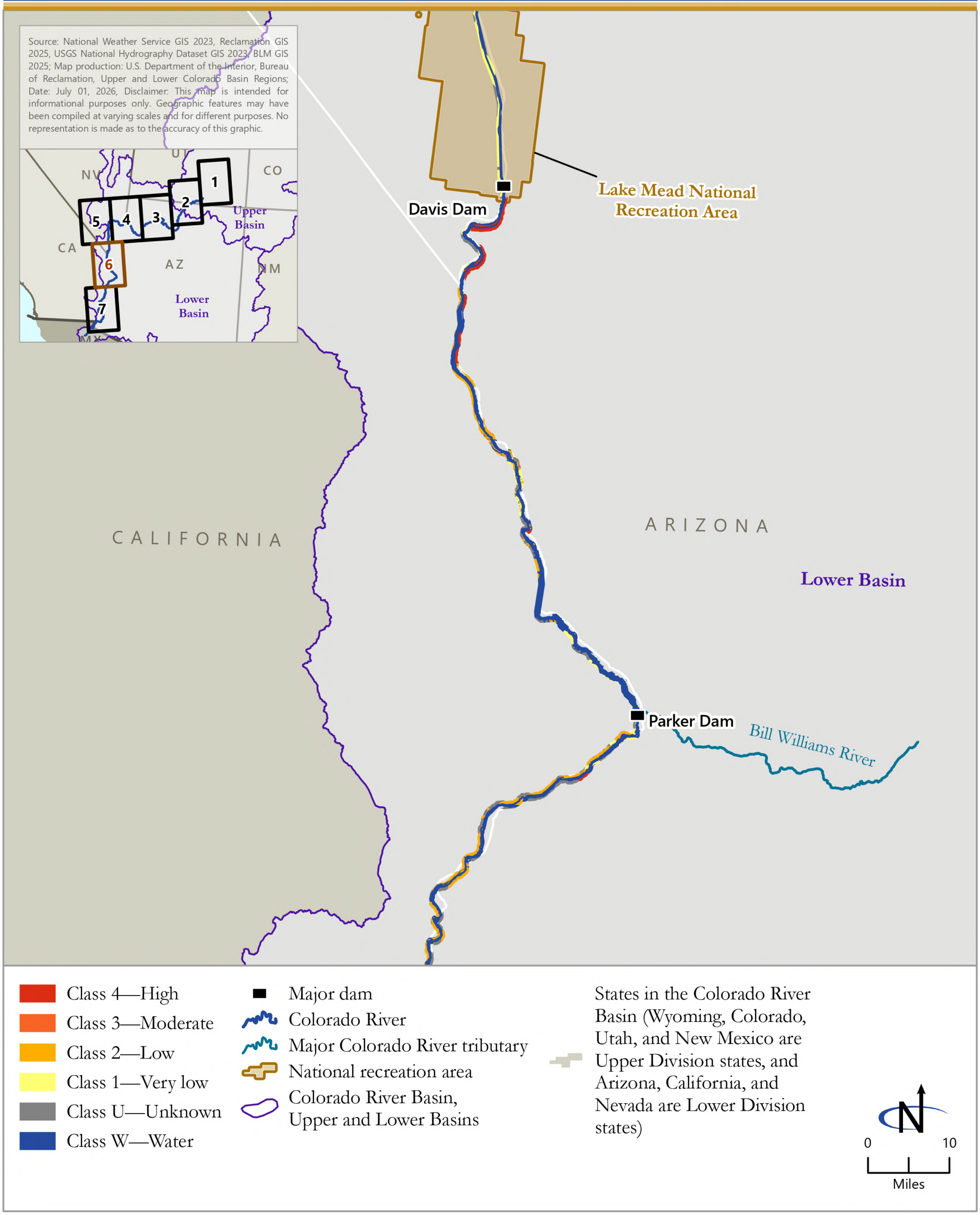
Map TA 12-7
Potential Fossil Yield Classification—Extent 6



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Map TA 12-8
Potential Fossil Yield Classification—Extent 7

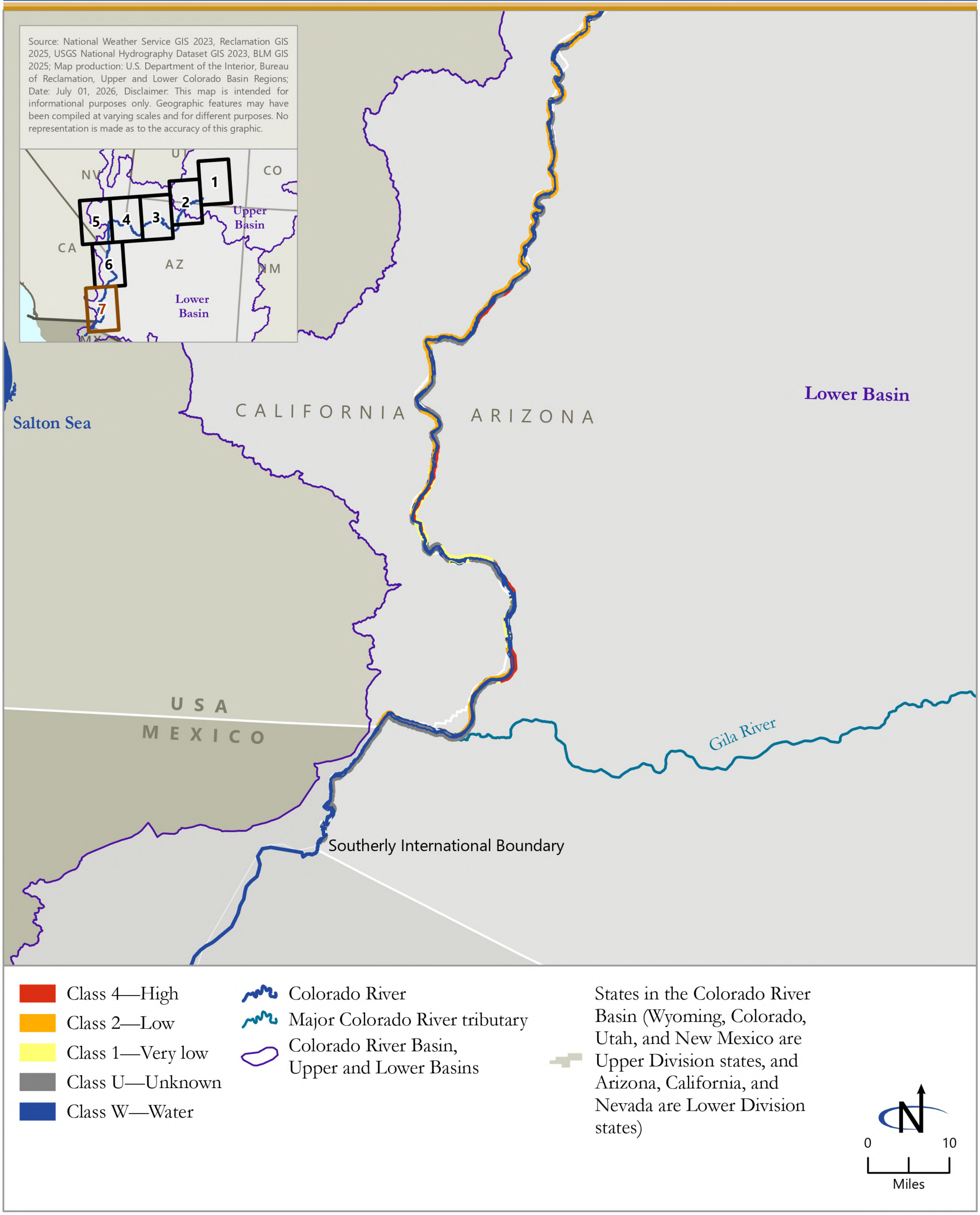


Table TA 12-2
Geologic Units of High and Very High PFYC Value within the Study Area

PFYC Value	Geologic Unit	Geologic Age
Glen Canyon National Recreation Area (NRA), including Lake Powell and the Colorado River with a 0.5-mile buffer		
4	Glen Canyon Group Glen Canyon Group (Navajo, Kayenta, Wingate, and Moenave Formations) and Nugget Sandstone Hoskinnini Sandstone Member Judd Hollow Tongue and Page Sandstone Tongues Kayenta Formation Kayenta Formation, undivided Lower red member, Virgin Limestone Member, and middle red member, undivided of the Moenkopi Formation Moenave Formation and Wingate Sandstone, undivided Moenkopi Formation Moenkopi, Dinwoody, Woodside, Thaynes, and other formations Moss Back Member of Chinle Formation Navajo Sandstone Navajo Sandstone of the Glen Canyon Group Page Sandstone Springdale Sandstone Member Summerville, Entrada, Carmel, Arapien, Twin Creek, and other formations Tropic Shale Upper member of Moenkopi Formation	Mesozoic
	Lower Cutler beds	Paleozoic
5	Church Rock Member of Chinle Formation Dakota Formation Monitor Butte Member of Chinle Formation Morrison Formation Morrison Formation Owl Rock and Petrified Forest Members of Chinle Formation Owl Rock Member of the Chinle Formation Petrified Forest Member of the Chinle Formation Shinarump Member of the Chinle Formation	Mesozoic
Glen Canyon NRA southwest boundary (approximately Marble Canyon) to Lake Mead NRA eastern boundary (majority is in the Grand Canyon National Park)		
4	Lower red member, Virgin Limestone Member, and middle red member, undivided of the Moenkopi Formation	Mesozoic
	Hermit Formation	Paleozoic

PFYC Value	Geologic Unit	Geologic Age
Lake Mead NRA, including Lake Mead and Colorado River with a 0.5-mile buffer		
4	Muddy Creek Formation, Fine-grained facies Muddy Creek Formation, Gypsum facies Muddy Creek Formation, Limestone facies Muddy Creek Formation, Tuff bed Sedimentary deposits	Cenozoic
	Hermit Formation Hermit Formation and Esplanade Sandstone, undivided	Paleozoic
Lower Colorado River from Davis Dam to SIB		
4	Chemehuevi Formation Chemehuevi Formation, gypsiferous mud Sedimentary deposits	Cenozoic
5	Tapeats Sandstone and Bright Angle Shale	Paleozoic

Source: BLM GIS 2025

Lake Powell and Glen Canyon Dam

The Glen Canyon NRA, encompassing portions of southern Utah and northern Arizona, contains one of the most extensive and complete sedimentary records on the Colorado Plateau. The stratigraphic sequence within Glen Canyon NRA exceeds 10,000 feet in cumulative thickness and represents approximately 300 million years of the earth's geologic history (Anderson et al. 2010). These strata chronicle a dynamic history that includes the assembly and breakup of the supercontinent Pangea, repeated transgressions and regressions of shallow inland seas, the development of vast eolian dune systems, and the incision of the modern Colorado River (Graham 2020). The resulting depositional environments—marine, fluvial, lacustrine, and eolian—record the complex interplay of tectonics, sedimentation, and biological evolution that shaped the region through Paleozoic, Mesozoic, and Cenozoic time.

Lake Powell, a reservoir formed by the impoundment of the Colorado River behind Glen Canyon Dam, occupies the central portion of Glen Canyon NRA. The reservoir extends approximately 186 miles and includes nearly 1,960 miles of shoreline with 96 major side canyons. Fluctuations in the lake level due to dam operations and hydrologic variation periodically expose new rock surfaces, revealing fossil-bearing strata that had been previously submerged (Milner et al. 2024). These exposures, along with naturally eroding canyon walls, make the area an important locality for the discovery and documentation of paleontological resources.

Glen Canyon NRA preserves fossil assemblages spanning the Paleozoic, Mesozoic, and Cenozoic Eras, offering insights into changing environments and biotic communities through time. Paleozoic formations, including the Kaibab Limestone and Toroweap Formation, contain abundant marine fossils, such as brachiopods, crinoids, and corals, which reflect deposition in warm, shallow marine environments during the Permian Period. Overlying Triassic units, such as the Moenkopi and Chinle Formations, record a transition to continental fluvial environments. These strata preserve vertebrate trackways, petrified wood, and early dinosaur remains, documenting faunal diversification following the Permian-Triassic extinction event. The Chinle Formation, in particular, is world-renowned for its early dinosaur tracksites and vertebrate assemblages, which record one of the earliest radiations of dinosaurs in North America (Graham 2016). Although there are limited areas mapped for the Coconino Sandstone, Toroweap Formation, Hermit Shale, Kaibab Formation, and Dinosaur Canyon Member of the Moenave Formation in the southern areas of Glen Canyon NRA—all known to be fossiliferous at localities outside Glen Canyon NRA—no fossils have been reported yet from any of these units in the recreation area (Milner et al. 2024).

The overlying Jurassic formations of the Glen Canyon Group—including the Wingate, Kayenta, and Navajo Sandstone—capture the transition from fluvial to eolian depositional systems. The Wingate and Kayenta Formations preserve small vertebrate fossils and trackways, while the Navajo Sandstone records a vast ancient dune field representing one of the largest preserved erg systems in the geologic record. These formations are particularly rich in vertebrate trace fossils, including extensive trackways of dinosaurs, reptiles, and amphibians (Milner et al. 2024). Many of these tracksites occur along the modern shoreline of Lake Powell, where fluctuating water levels periodically uncover new fossil surfaces.

In 2023, receding lake levels revealed a previously submerged fossil locality within the Navajo Sandstone, where paleontologists discovered a tritylodontid mammaliaform bonebed dating to approximately 180 million years ago. This discovery represents one of the most complete early mammal-relative assemblages yet documented in the Navajo Sandstone and provides valuable insight into vertebrate evolution during the Early Jurassic (NPS 2023).

Cretaceous formations, including the Naturita Formation and Tropic Shale, preserve a record of the Western Interior Seaway and contain marine invertebrates, plant fossils, and marine reptiles, illustrating the return of widespread marine conditions during the mid-Cretaceous (Titus et al. 2016). Alcoves, including the best-known Quaternary site (Bechan Cave), are important fossil sites associated with fossil dung in Glen Canyon NRA. Fossil pollen and plant macrofossils preserved in packrat middens and dung deposits further document ecological and climatic changes during the Late Quaternary (Graham 2016; Mead et al. 2020).

Glen Canyon NRA staff is completing a paleontological resources inventory survey; because of the size of the recreation area, the survey is being done in phases, with the latest phase completed in 2024. The three inventory reports provide the baseline data for the breadth of paleontological resources found from Glen Canyon NRA. Despite these efforts, natural processes, such as erosion, mass wasting, and fluctuating water levels, continue to expose and degrade fossil-bearing strata. Additionally, anthropogenic influences, including reservoir sedimentation, vandalism, and unauthorized fossil collection, pose ongoing threats to resource preservation (Graham 2016; Santucci et al. 2009). In some areas, sediment accumulation resulting from dam operations may enhance fossil preservation by burial, while in others, it obscures or prevents discovery. Consequently, Glen Canyon NRA represents a dynamic and scientifically valuable setting where both natural and human processes continually shape the exposure, preservation, and accessibility of paleontological resources.

Grand Canyon National Park

The Colorado River corridor of Grand Canyon National Park contains paleontological resources of exceptional scientific significance, spanning nearly 1.2 billion years of the earth's history. The river corridor is renowned for its dramatic display of geomorphic effects created by fluvial incision and its unique dry preservation of fossils from the Ice Age (Mead et al. 2020). The river channel serves as the physical axis along which the park's oldest and youngest fossil-bearing strata are exposed. The river channel is organized into two principal paleontological occurrences documented in the Grand Canyon National Park Centennial Paleontological Resource Inventory (Santucci and Tweet 2021): ancient body and trace fossils preserved within the canyon's deep bedrock formations, and Pleistocene and Holocene fossils recovered from dry caves and sediment deposits along the corridor walls.

The oldest fossil-bearing rocks in the park are exposed along the river's edge in the eastern and central canyon. Precambrian sedimentary units of the Grand Canyon Supergroup (Bass Formation, Hakatai Shale, Dox Formation, Galeros Formation, and Kwagunt Formation) preserve stromatolites, acritarchs, and vase-shaped microfossils representing some of the earliest evidence of life documented in the National Park System, beginning approximately 1.25 billion years ago (Santucci and Tweet 2021). Above these, Cambrian units of the Tonto Group (Tapeats Sandstone, Bright Angel Shale, and Muav Limestone) are among the most fossil-rich formations accessible from the river corridor, preserving abundant invertebrate trace fossils, including burrows, trails, and feeding traces, as well as body fossils such as trilobites and brachiopods (Santucci and Tweet 2021). The Temple Butte Formation, exposed in isolated channel-cut pockets near the river in portions of the canyon, yields Devonian fish remains representing the earliest vertebrate fossils in the park (Santucci and Tweet 2021).

The river corridor is equally significant for its Pleistocene and Holocene fossil record. Dry caves and alcoves embedded in the corridor walls create the arid, sheltered conditions necessary to preserve organic material in exceptional detail (Mead et al. 2020). Among the most significant localities is Sandblast Cave, where excavations produced important data on the California condor, including a preserved nest, in addition to specimens of extinct mountain goat, bison, camel, and horse, along with the only reported mammoth remains from the Grand Canyon (Mead et al. 2020). Other fossil-bearing localities along the corridor include Stanton's Cave, Little Nankoweap, Skylight Cave, Hummingbird Cave, and Rampart and Vulture Caves in the western canyon, where thick deposits of Shasta ground sloth dung, hair, and skin were recovered (Mead et al. 2020). Packrat middens from these sites yield plant macrofossils, pollen, insects, and small vertebrate remains that document ecological and climatic shifts across the late Pleistocene and into the Holocene (Mead et al. 2020).

The objective of the Grand Canyon National Park Centennial Paleontological Resource Inventory was to identify the scope, significance, distribution, and management issues associated with fossils in the park (Santucci and Tweet 2021). The river corridor presents particular management challenges due to its difficult terrain and limited accessibility, and the inventory acknowledges that systematic survey of inner canyon fossil localities remains incomplete. Despite this, the Colorado River corridor constitutes one of the most scientifically valuable zones within Grand Canyon National Park.

Lake Mead and Hoover Dam

The Lake Mead NRA encompasses a geologically diverse landscape extending across portions of southeastern Nevada and northwestern Arizona. The stratigraphic record within Lake Mead NRA spans from the Paleozoic through Cenozoic Eras, representing more than 500 million years of the earth's history (BLM GIS 2025; Beard et al. 2007). These rocks preserve an array of marine, fluvial, and terrestrial depositional environments that document the evolution of the southwestern margin of the North American continent and provide an exceptional record of paleontological change through geologic time.

Fossils in Lake Mead NRA span the Paleozoic, Mesozoic, and Cenozoic Eras. Marine fossils such as trilobites and Cenozoic bivalves can be found along the Cottonwood Wash in Lake Mead, representing a crucial moment in the emergence of multicellular life on earth. As terrestrial landscapes dried up into the Jurassic Period 180 million years ago, present-day Lake Mead underwent a period of extensive erosion that resulted in a geological gap between the rock record of fossils until the later portion of the Cenozoic Era. Lake Mead has an impressive list of fossils documented from the Oligocene Epoch of the Cenozoic Era, particularly in the forms of mammals, amphibians, birds, and reptiles (NPS 2022).

The NPS completed a comprehensive paleontological resource inventory for Lake Mead NRA in 2018. While this inventory is confidential to the NPS, it established baseline data for fossil-bearing formations, recorded known localities, and assessed the relative potential for new discoveries. The report concluded that several formations have high fossil potential and merit continued monitoring and research. This inventory is the most recently completed report for the NRA.

Fluctuating lake levels have a direct influence on fossil exposure and preservation within Lake Mead NRA. Periods of low water levels at Lake Mead have exposed previously submerged geologic formations, resulting in increased accessibility to fossil-bearing strata along the shoreline. These exposures, while scientifically valuable, are also vulnerable to erosion and visitor impacts. As water levels fluctuate, cycles of inundation and exposure accelerate mechanical weathering and can lead to disarticulation or loss of fossil specimens. Conversely, sediment deposition in shallow nearshore zones may help preserve fossils by rapid reburial under fine-grained sediments.

Continued reductions in lake elevation are expected to expose additional outcrops of fossil-bearing formations, particularly along the upper reaches of the reservoir and tributary canyons. The NPS has identified these newly emergent areas as priorities for future surveying and monitoring. Overall, Lake Mead NRA contains a high diversity of paleontological resources, including the Miocene Horse Spring Formation, Muddy Creek Formation, and Pliocene and Pleistocene river gravels, that span marine, fluvial, and terrestrial systems, making it one of the most scientifically significant and geologically varied regions in the southwestern U.S.

Lower Colorado River Corridor

The lower Colorado River corridor follows the Colorado River from southern Nevada to the international border with the United Mexican States. Reclamation completed a paleontological resources inventory of the entire corridor in 2020 (Bonde and Slaughter 2020). The inventory report is confidential to Reclamation because it includes paleontological localities; however, the information gained from this inventory expanded the knowledge of the paleontological record for the entire river corridor.

The sedimentary geologic record for the lower Colorado River corridor extends from the Middle Cambrian to the Pleistocene. While the geologic record is not fully continuous, units representative of most periods of geologic time are present in this area (Bonde and Slaughter 2020).

Current Conditions

Fluctuating water levels in both Lake Mead and Lake Powell pose significant threats to paleontological resources, including fossils and trackways preserved in sedimentary rocks. In reservoirs, cycles of inundation and exposure cause softer rocks like sandstone, which often contain delicate trackways, to become friable and more prone to erosion. As water levels drop, previously submerged fossils are exposed to environmental forces such as wind, sun, and temperature fluctuations, which accelerate the fossils' degradation. While sediment deposition can temporarily protect some sites, the exposure of fossil-rich layers as water levels recede increases the likelihood of weathering, fragmentation, and disturbance from human activity.

In addition to direct threats to fossils, fluctuating water levels disrupt the stability of sediment layers crucial for preserving these paleontological resources. The disturbance of these sediments destabilizes both the fossils themselves and the broader habitats they rely on. Sensitive plant species, animal burrows, and other ecological components can be damaged or destroyed as human activity increases in exposed areas. The exposure of fossil-rich sites also encourages further human impacts, such as increased recreational activities (hiking, off-highway vehicle use, and unauthorized fossil collection), which lead to soil compaction, vegetation trampling, and pollution from waste and chemicals, all of which undermine preservation efforts and hasten degradation.

Lands in the study area are subject to fluctuating water levels under current conditions. Water is a catalyst for erosion and a popular outlet for recreation. Possible water-related impacts that result in the threat or loss of paleontological resources in the study area include the following:

- Flooding events or controlled capture of reservoir levels lead to the elevation of water levels and consequent submersion of fossil-bearing rock layers.
- The controlled release of reservoir waters results in an increase in river velocity and downstream erosion rates, consequently removing fossil resources preserved in the geologic units that line the river corridors.
- Water systems are often associated with areas of high topographic relief formed from downcutting by a water source (that is, the steep canyon walls of the Grand Canyon carved by the Colorado River); these areas of high topographic relief are subject to higher rates of erosion and potential resources lost versus areas of lower topographic relief.
- Rivers and reservoirs are highly associated with recreation. The high density of people and popular use of public lands along the lower Colorado River may unintentionally invite theft, vandalism, or disturbance to fossil resources exposed along the margins of the waterways (Reclamation 2020).

Erosion is the primary agent that exposes paleontological resources on the surface to then await discovery and documentation. Lake Powell and Lake Mead are interconnected; adjustments of water releases at Lake Powell have a downstream effect on Lake Mead. The impacts on paleontological resources due to natural processes are the same at both reservoirs, but the intensity at which they occur and to what resources they occur vary. Paleontological resources in Glen Canyon NRA are largely more understood and considered to be highly scientifically important. As depicted in **Figure TA 12-8**, most of the area is ranked PFYC 4 (high) or PFYC 5 (very high). This is true at the mapped shorelines. In Lake Mead, the paleontological resources are less understood, and much of the shoreline is mapped PFYC U (unknown; **Figure TA 12-12**). Erosion concerns at Lake Powell are extremely high because erosion and other natural processes are impacting the geologic units with known high and very high paleontological value.

TA 12.2 Environmental Consequences

TA 12.2.1 Methodology

Changes in lake levels or river flows from the annual releases could directly and indirectly impact paleontological resources. Of greatest concern are effects on paleontological resources that degrade or that damage those resources before the resources can be preserved. Direct impacts may occur from processes such as wave action and wet-dry cycling. Direct impacts include any impact that is immediate in place and time; indirect impacts, such as those from increased visitation, are those that occur later in time.

Impacts on paleontological resources analyzed in this section only include those from Reclamation’s management of the water in Lake Powell and Lake Mead. Two types of analyses are used to evaluate potential impacts on paleontological resources: preservation risk modeling developed by the U.S. Geological Survey (USGS) and NPS and aeolian transport-vegetation cover–high-flow experiment (HFE) joint modeling also developed by the USGS. Additionally, PFYC data were used to analyze areas of high fossiliferous potential within the study area.

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

PFYC System

Paleontological localities were not used in this analysis because they are confidential and information is limited for an analysis at this scale. Instead, the BLM’s PFYC system was used. As described above, the PFYC system is a tool used to predict impacts on fossil resources from planned actions. The system is straightforward: some rock units are more likely to contain scientifically interesting fossils than others. The assessment can be made by rock type and generalized from previously recorded fossil discoveries. The system is simple, ranked from 1 (very low potential) to 5 (very high potential), with a “U” category for unknown or understudied areas. The PFYC system is continuously updated by the BLM and other agencies, and it was used to map the entire study area.

Preservation Risk Modeling

The USGS, in cooperation with the NPS, developed a preservation risk model for paleontological resources at or below full-pool elevations at Lake Powell and Lake Mead (Caster et al. 2026). The preservation risk model is a spatial model that considers several landscape characteristics, locations of previously recorded paleontological resources, and the potential for water-related impacts such as wave action and erosion. The USGS mapped the shoreline areas and ranked the preservation risk from 1 (low) to 5 (high) based on low to high potential for resource preservation to be affected by water at a given reservoir elevation. The ranking incorporates two other models: (1) the PFYC system, which identifies where paleontological resources are more likely or less likely to be found, and (2) the Preservation Hazard Model, which identifies where site impacts related to lake fluctuations will likely occur.

The Preservation Hazard Model is based on the simplified physical factors influencing lake shore geomorphic change. Similar to coastal environments, wave action drives erosion, but reservoirs have the added risk of large, rapid, and sustained changes in water level that affect runoff base levels, soil deformation, and chemical weathering through submersion and exposure. These aspects were incorporated into the model using available USGS topography and bathymetric data and the known relationships between slope-wave interactions, base level adjustments, lake fetch lengths, and lake shoreline area change, as well as a given volume of reservoir storage loss. In this model, the highest rank (5) corelates to a higher potential for impacts, and the lowest rank (1) correlates to a lower risk from these factors. Human impacts, such as vandalism or unauthorized collection, are not included in this model.

When combining the PFYC and Preservation Hazard Models, a simple rule was used based on the assumptions that (1) regardless of hazard rank, areas likely to contain resources have the potential to be affected by lake management actions; (2) even where resource likelihood is low, hazards from water levels can impact a potentially significant resource; (3) areas with a very high likelihood of containing resources and a very high potential for impacts are at the highest risk of resource condition changes; and (4) areas with a very low likelihood of containing resources and a very low potential for impacts are at the lowest risk of resource condition changes.

The Preservation Hazard Model uses the same ranking system as the PFYC system. However, preservation risk ranks 1–5 are not equivalent to PFYC ranks 1–5.

Wind-Deposited Sediment

Research conducted by the USGS and NPS has demonstrated that wind-deposited (aeolian) sediment can help stabilize and preserve paleontological sites along the Colorado River over long periods of time (Santucci et al. 2009). Sediment is generally deposited via wind on nearby terraces at an average of a few millimeters a year; however, Glen Canyon Dam operations can inhibit the formation of sandbars from which the sediment is blown. Management of the Colorado River influences the supply of windblown river sand in two ways: (1) the reduction of river flows below current average baseflow levels causes sand in the river channel to be exposed subaerially, and given sufficient time, can dry out and become available for wind transport; and (2) when HFEs are successfully implemented to rebuild river sandbars, the sand in the subaerial portion of the sandbars becomes available for wind transport. However, riparian vegetation can block the windblown transport of sand; when cover decreases, the potential for wind transport increases.

The analysis integrated three independent models: the aeolian sand availability model (hereafter referred to as the "Sand Area Model" by Kasprak et al. 2024), the Vegetation Habitat Suitability Model (Butterfield et al. 2018), and the Sandbar Volume Model (modified from Mueller and Grams 2021). The Sand Area Model was specifically developed to predict the supply of river-sourced, windblown sand as a function of river discharge and subaerial exposure time; however, the Sand Area Model used here does not incorporate changes in vegetation cover that occur as a function of river hydrology or geomorphic changes (deposition and erosion of sand) that would also affect sand area. Therefore, the Sand Area Model was coupled with outputs from the Marble Canyon Vegetation Habitat Suitability Model (Kelley et al. 2026). Scenarios were assessed in which modeled sand availability exceeded a defined threshold while vegetation suitability remained below a specific benchmark, indicating conditions favorable for aeolian transport.

To account for the dynamic influence of high-flow events, which can increase sandbar volume and enhance future sand supply, the Sandbar Volume Model output was then incorporated. In this analysis, a future is defined as a "preferred minimum performance" if one of the following logical criteria was met: (1) the Sand Area and Vegetation Habitat Suitability Models simultaneously exceeded and fell below their respective thresholds (suggesting favorable conditions for aeolian transport), or (2) the Sandbar Volume Model exceeded the threshold, indicating enhanced sand supply via fluvial-related deposition. Previous studies suggest that dam releases that allow these conditions to be met 1–3 years may slow the rate of degradation to enable time for mitigation and planning. Considering temporal variability of future acceptability, it is ideal if these conditions are met at least once every 3 years. Model thresholds were derived from recent historical baselines; the sand area and vegetation (Marble Canyon only) thresholds reflect the 50th percentile of model outputs from 2000 to 2023, while the sandbar volume threshold is set at 1.5 times the modeled initial condition beginning in 2027.

Impact Analysis Area

The impact analysis area for paleontological resources consists of the Colorado River corridor from the upper limits of Lake Powell, through the Grand Canyon and Lake Mead, and from Hoover Dam to the SIB.

Assumptions

- The analysis of physical impacts on paleontological resources resulting from changes in lake levels, river flows, and sediment changes is informed by the cultural resources analysis.
- Impacts on paleontological resources can be characterized based on projected lake elevations and river flows.
- The impact analysis area includes known, unrecorded, and predicted paleontological resources that may be submerged or exposed and those geologic units that are sensitive for the presence of scientifically important paleontological resources.
- Specific paleontological locations are not discussed in this analysis, but the level of information available is assumed to be sufficient for this broadscale analysis.

- The exposure of paleontological resources may lead to the discovery of scientifically important fossils; however, the process and practical means of recovering paleontological resources within the reservoirs or along the Colorado River channel are limited.
- Landforms with steeper slopes are more susceptible to wave action erosion compared with low-slope areas.

Impact Indicators

- End-of-year lake elevations that may expose paleontological resources to damage from wave action, wet-dry cycling, increased visitation, and unauthorized collection or vandalism
- Changes in river flows that may contribute to erosion and exposure of resources that may expose fossils and trackways to damage from erosion, wet-dry cycling, or increased visitation
- Increase or decrease in sandbar building and availability of windblown sediments to protect paleontological localities or exposed fossils

Summary of Impact Mechanisms

This section provides a high-level summary of the primary physical, environmental, and human-related mechanisms through which changes in reservoir elevations and river flows may affect paleontological resources within the impact analysis area. Paleontological resources in Lake Powell, in Lake Mead, and along the Colorado River corridor may be affected by processes associated with reservoir inundation and exposure, shoreline and channel erosion, sediment transport, weathering, and changes in human access. **Table TA 12-3** summarizes these mechanisms and describes the general ways in which each can affect the preservation, stability, and scientific integrity of fossils and trackways. The table is intended to orient the reader to the types of impacts evaluated in this chapter and does not distinguish differences in impact magnitude or severity among the alternatives, which are addressed in subsequent sections.

Table TA 12-3
Paleontological Resource Impact Mechanisms

Impact Mechanism	Description of Mechanism	Summary of Impacts on Paleontological Resources
Reservoir inundation and exposure	Fluctuations in Lake Powell and Lake Mead reservoir elevations alternately submerge and expose paleontological resources along shorelines and reservoir margins.	Repeated exposure increases vulnerability to physical and chemical degradation of fossils and trackways. Continuous inundation generally preserves paleontological resources more effectively than repeated cycles of exposure and inundation.
Wave action	Wind-driven wave energy acts on shoreline slopes and exposed reservoir margins, particularly where fetch length and slope increase wave power.	Mechanical erosion from wave action can undercut fossil-bearing strata, abrade exposed surfaces, and displace or destroy fossils and trackways, resulting in the loss of scientific context.

Impact Mechanism	Description of Mechanism	Summary of Impacts on Paleontological Resources
Wet-dry cycling	Reservoir drawdown and refill cause alternating periods of submersion and exposure.	These cycles accelerate the breakdown of fossil-bearing rock, particularly softer lithologies such as sandstone; this breakdown leads to cracking, spalling, loss of surface detail, and reduced integrity of fossils and track surfaces.
Chemical weathering	Prolonged contact with water followed by exposure to oxygen and atmospheric conditions breaks down or molecularly alters paleontological resources.	The weathering alters the mineral composition of enclosing rock, increasing friability after exposure and contributing to long-term degradation of fossils, even where physical erosion is limited.
Sunlight and ultraviolet exposure	Following reservoir drawdown, there is direct solar radiation on newly exposed fossil surfaces.	This exposure promotes surface weathering and thermal stress that can weaken fossil-bearing rock and accelerate degradation of exposed fossils and trackways.
Freeze–thaw processes	Seasonal temperature fluctuations allow water within fractures to freeze and expand, then thaw and contract.	These processes expand fractures and weaken rock matrices, increasing the likelihood of breakage, detachment, or loss of fossil material from outcrops.
Wind erosion	Wind acts directly on exposed sediments and fossil surfaces along reservoir margins and river terraces.	Wind erosion removes fine sediments that may otherwise protect fossils, abrades exposed surfaces, and increases rates of fossil degradation.
Fluvial erosion and deposition	Changes in river flows alter erosion and sediment deposition patterns along the Colorado River corridor.	Increased erosion can expose or damage fossils and trackways, while deposition and burial by fluvial sediments can temporarily protect paleontological resources from weathering and disturbance.
Aeolian sediment deposition	Windblown sand from exposed sandbars and river sediments accumulates on adjacent terraces and slopes.	Burial by aeolian sediments can stabilize and preserve paleontological resources over long periods by reducing exposure to erosion, weathering, and human disturbance.
Vegetation cover changes	Changes in river flows and sediment supply influence riparian vegetation extent, affecting windblown sediment transport.	Increased vegetation can limit aeolian sediment transport and reduce the natural burial of fossils, while reduced vegetation can enhance sediment deposition and protective burial.
Human access and visitation	Lower reservoir elevations expand exposed shorelines and increase accessibility by recreationists.	Trampling, inadvertent disturbance, vandalism, and unauthorized fossil collection may increase, resulting in loss of scientific context and irreversible damage to paleontological resources.

Impact Mechanism	Description of Mechanism	Summary of Impacts on Paleontological Resources
Unauthorized collection and vandalism	There can be intentional or opportunistic removal or defacement of exposed fossils.	Unauthorized collection permanently remove fossils from their geologic context, resulting in irreversible loss of scientific and educational value.

Note: This table provides a qualitative summary of impact mechanisms and does not distinguish differences in severity among the alternatives.

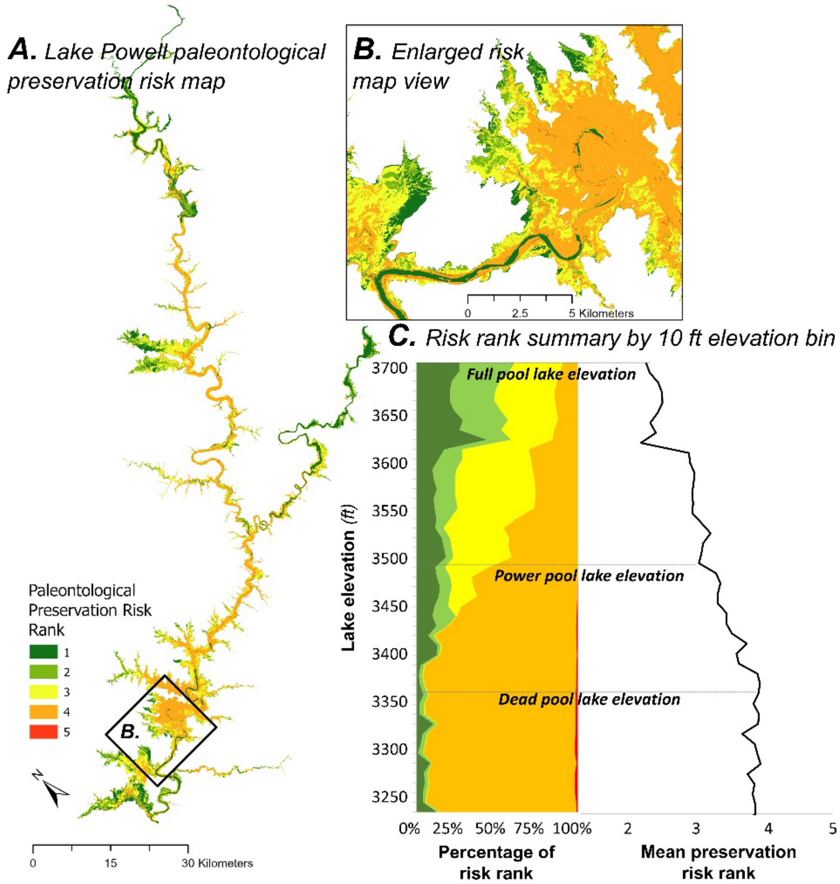
TA 12.2.2 Issue 1: How will fluctuations in water levels due to changes in dam operations (primarily in Lake Powell and Lake Mead) impact the exposure, erosion, and degradation of paleontological resources, including fossils and trackways?

The USGS, in cooperation with the NPS, created the Paleontological Preservation Hazard Model, which was used in the decision-making under the DMDU modeling process. This spatial model summarizes 10-foot-elevation bins in Lake Powell and 5-foot-elevation bins in Lake Mead, so that each elevation from full pool to empty has a preservation risk rank. Next, projected monthly lake elevations are related to those elevation bins to estimate the preservation risk rank. **Figure TA 12-3**, below, below depicts the relationship between lake elevation and preservation risk rank at Lake Powell (Caster et al. 2026). This relationship is consistent with general reservoir conditions; the same trend is true for Lake Mead (the risk rises as elevations fall).

As lake elevations decrease, paleontological preservation risk increases. The threshold for preservation risk at each reservoir was derived from the 90th percentile values of the 2008–2024 LTEMP. At Lake Powell, for example, the threshold is 2.93, which occurs at approximately 3,600-foot elevation. The more time that a risk rank is exceeded (in this case, the more time that lake elevations remain below 3,600 feet), the more paleontological resources that have likely never been exposed may become exposed. Those resources are subjected to higher preservation hazards than any time since the reservoir was filled.

Fluctuations in water levels due to changes in dam operations at Lake Powell and Lake Mead could significantly impact paleontological resources, particularly fossils and trackways found in sedimentary formations like sandstone. These resources are vulnerable to erosion, weathering, and degradation when exposed repeatedly as water levels rise and fall. Specific studies of paleontological sites and effects of inundation have not been conducted at Lake Powell or Lake Mead. Anecdotal evidence from field staff indicates that sandstone becomes friable and crumbly after periods of inundation and exposure. It is assumed that certain types of paleontological resources, especially trackways in softer bedrock such as sandstone, could be destroyed or severely affected by the inundation and exposure, resulting in loss of rock outcrop integrity. However, it is unclear whether greater damage is caused only by a single inundation event or by repeated cycles of inundation and exposure. It is assumed that paleontological resources, including fossils and trackways, will experience similar impacts as those paleontological resources subjected to similar processes.

Figure TA 12-3
Risk Rank Summary at Lake Powell



Source: Caster et al. 2026

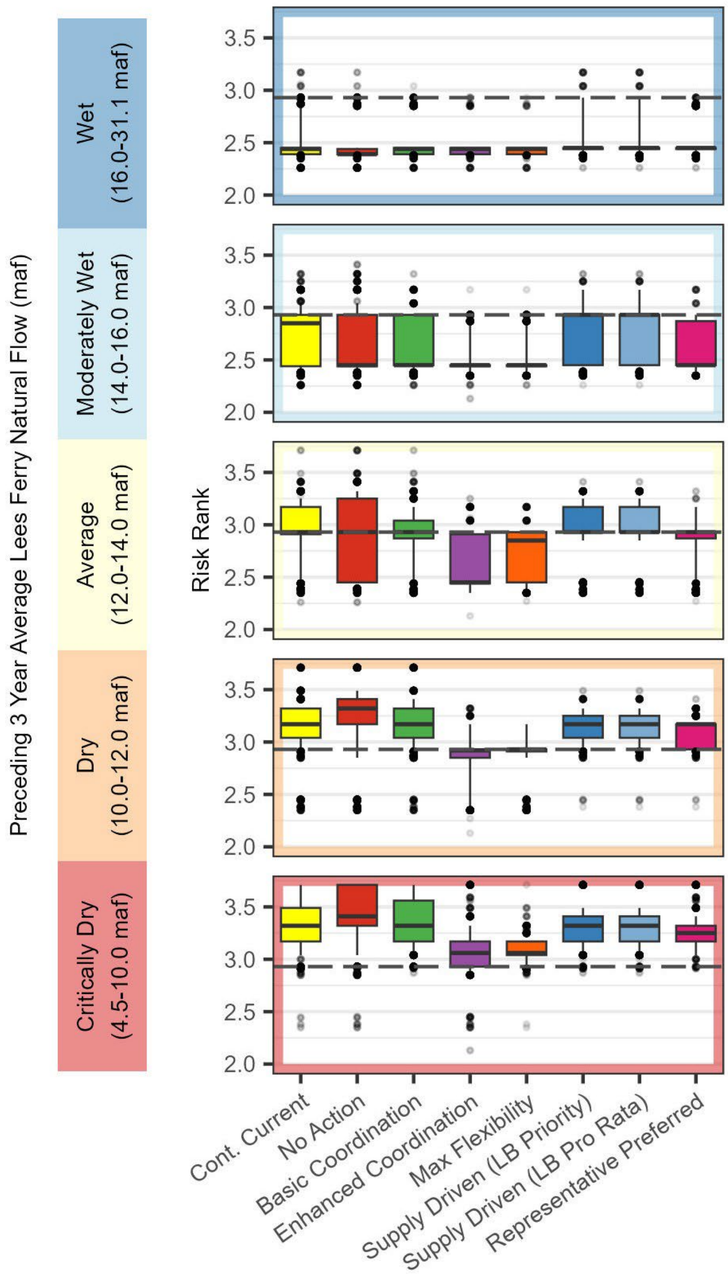
Lake Powell

This section presents a comparison of the No Action Alternative, Continued Current Strategies (CCS) Comparative Baseline, and action alternatives with respect to the paleontological preservation risk at Lake Powell. **Figure TA 12-4**, below, looks at the response of paleontological preservation risk in Lake Powell to different hydrologic conditions under different alternatives by looking at the preceding 3-year average of Lees Ferry natural flow. The figure presents the preservation risk rank values in a conditional box plot panel. The bold center line of each box represents the median value, the top and bottom of each box captures the 25th to 75th percentile of the modeled results, the lines extend to the 10th and 90th percentiles, and the outliers are represented as dots beyond these lines. In each flow category shown in the box plot, the historically derived threshold is identified with a dashed line.

Note that the performance of the Supply Driven Alternative (both Lower Basin Priority [LB Priority] and Lower Basin Pro Rata [LB Pro Rata] approaches) will not differ for the Lake Powell preservation risk because they use the same operation of Lake Powell. See **Table TA 12-4** at the end of this technical appendix for the statistical breakdown of preservation risk rank at Lake Powell for each hydrologic condition and alternative, including the maximum, 90th percentile, 75th percentile, median, 25th percentile, 10th percentile, and minimum preservation risk rank.

In the Average Flow Category, the Maximum Operational Flexibility Alternative and Enhanced Coordination Alternative have similar ranges that are around or below the threshold. However, the Enhanced Coordination Alternative has a median risk value that is approximately 14 percent lower than what is modeled for the Maximum Operational Flexibility Alternative (2.45 and 2.85, respectively). In the Dry Flow Category, the Enhanced Coordination Alternative and Maximum Operational Flexibility Alternative perform similarly well, although all alternatives exceed the historically derived threshold under the Critically Dry Flow Category.

Figure TA 12-4
Water Year Maximum Paleontological Preservation Risk at Lake Powell



In all flow categories, the Basic Coordination Alternative has similar medians to the CCS Comparative Baseline and No Action Alternative. Under the Average Flow Category, the No Action Alternative has greater variability, while the Basic Coordination Alternative and CCS Comparative Baseline perform almost identically. All medians are at the historically derived threshold (see **Table TA 12-4**).

The Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) exceeds the historically derived threshold at the Average Flow Category and wetter conditions, with medians at or above 2.93. In the Wet Flow Category, the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches), Basic Coordination Alternative, No Action Alternative, and CCS Comparative Baseline still have outliers that exceed the historically derived threshold. At Lake Powell, the Enhanced Coordination Alternative results in the least variability and most values below the threshold.

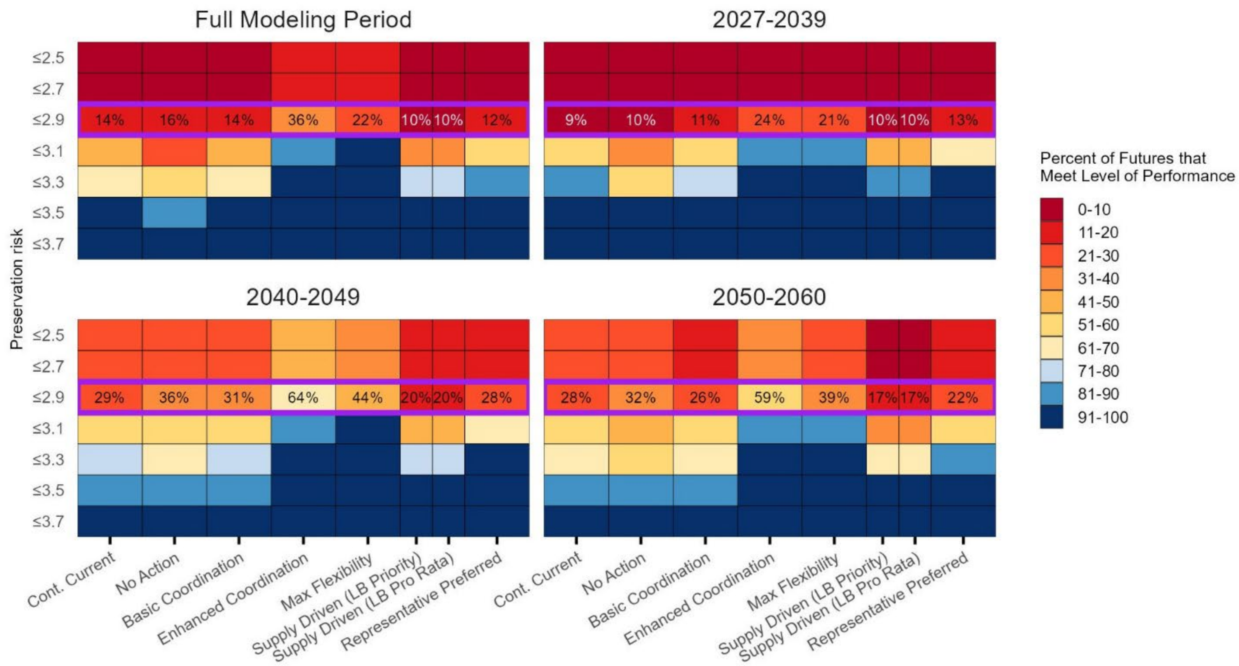
The Representative Preferred Alternative generally performs in the middle of the range of alternatives; it performs slightly better than the Supply Driven Alternatives and slightly worse than the Maximum Operational Flexibility Alternative. At Lake Powell, the Representative Preferred Alternative does not perform notably for preserving paleontological resources.

Figure TA 12-5, below, depicts the performance of each alternative with respect to keeping paleontological preservation risk ranks at Lake Powell below the historically derived threshold in at least 90 percent of months. This is the same threshold that what was used in **Figure TA 12-4**. The figure is broken into four heat maps, each showing a different time period during the analysis: the top left heat map shows the full modeling period from 2027 through 2060, and the remaining three panels show subperiods. Rows of the heat map show different preservation risk ranks, with higher rows corresponding to lower (more challenging) ranks. The highlighted row captures the percentage of futures that an alternative achieves a rank of 2.9 in 90 percent of the months (futures equal modeled hydrologic scenarios).

The Enhanced Coordination Alternative is the most robust at achieving a risk rank of 2.9 in 90 percent of months over the full modeling period, doing so in 36 percent of the futures. The Basic Coordination, No Action, and Representative Preferred Alternatives perform similarly to the CCS Comparative Baseline, succeeding in 14 percent, 16 percent, 12 percent, and 14 percent of futures, respectively. The Maximum Operational Flexibility Alternative succeeds 22 percent of the time over the full modeling period, which is just similar enough to the CCS Comparative Baseline and the No Action Alternative. The Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) has the least robust success rate over the full modeling period at 10 percent.

In lower rows of the heat maps, the Maximum Operational Flexibility Alternative begins to perform better as the preservation risk increases than the Enhanced Coordination Alternative; the Maximum Operational Flexibility Alternative consistently achieves 91–100 percent robustness by 3.1 and 3.3, respectively, over the full modeling period. The other alternatives reach 91–100 percent robustness at 3.5 while the CCS Comparative Baseline reaches 91–100 percent robustness at 3.7.

Figure TA 12-5
Paleontological Resources in Glen Canyon NRA: Robustness.
Percentage of Futures in Which Monthly Preservation Risk Stays Below the Value Specified in Each Row in at Least 90 Percent of Months

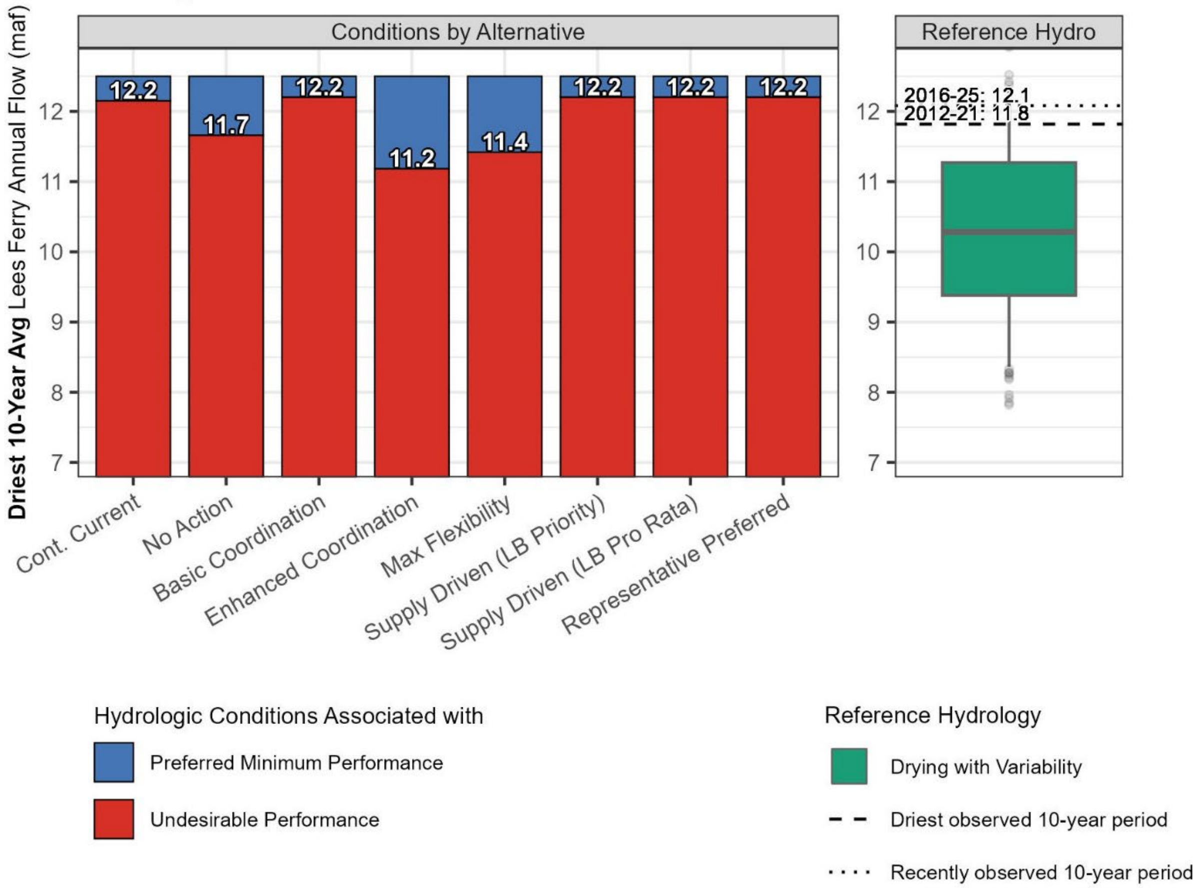


In the first decadal subperiod, the Enhanced Coordination and Maximum Operational Flexibility Alternatives meet the historically derived threshold in 24 percent and 21 percent of futures, respectively. Given the planned length of this decision, it is notable that the Representative Preferred Alternative meets the historically derived threshold in only 13 percent of futures between 2027-2039. This suggests that existing challenges related to reservoir fluctuations at Lake Powell, including exposure, erosion, and degradation of paleontological resources, will continue under all alternatives.

Figure TA 12-6, below, looks at flow conditions that could cause the preservation risk rank to exceed the historically derived threshold in more than 10 percent of months of the 34-year modeling horizon. The driest 10-year average Lees Ferry natural flow was identified as a good predictor of undesirable performance; this is shown in the reference hydrology panel along with the recently observed 10-year average flow.

The Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) results in undesirable performance (that is, it becomes vulnerable to paleontological preservation risk rank exceeding the historically derived threshold), when the future includes a 10-year average flow of 12.2 maf or lower. Nearly all reference hydrologic traces include average flows of 12.1 or lower; the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) results in futures where paleontological resources are most vulnerable to increased risk.

Figure TA 12-6
Paleontological Resources in Glen Canyon NRA: Vulnerability.
Conditions that Could Cause Risk to Paleontological Sites in Lake Powell Exceeding Historical Benchmark More than 10 Percent of Months



The Enhanced Coordination Alternative results in undesirable performance when the 10-year average flow is below 11.2 maf. Approximately 75 percent of the reference hydrologic traces include averages this low or lower. The No Action Alternative and Maximum Operational Flexibility Alternative perform similarly to the driest 10-year average flow from 2012 to 2021 (11.7 maf and 11.4 maf, respectively). Under these alternatives, paleontological resources are vulnerable to conditions that are close to what has already occurred.

The CCS Comparative Baseline and the Basic Coordination, Supply Driven (both LB Priority and LB Pro Rata approaches), and Representative Preferred Alternatives perform the same, with paleontological resources becoming vulnerable at approximately 12.2 maf. Nearly 100 percent of the reference hydrologic traces include average flows this low or lower, so the vulnerability is very high.

Lake Mead

This section presents a comparison of the No Action Alternative, CCS Comparative Baseline, and action alternatives with respect to paleontological preservation risk at Lake Mead. **Figure TA 12-7**, below, looks at the response of paleontological preservation risk in Lake Mead to different hydrologic conditions under different alternatives by looking at the preceding 3-year average of Lees Ferry natural flow. The figure presents the preservation risk rank values in a conditional box plot panel. The historically derived threshold at Lake Mead is a risk rank of 2.33. Note that the performance of the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) will not differ in Lake Mead preservation risk because the modeling assumes no banking activity. See **Table TA 12-5** at the end of this technical appendix for the statistical breakdown of preservation risk rank at Lake Mead for each hydrologic condition and alternative.

In each flow category shown in the box plot, the historically derived threshold (2.33) is identified with a dashed line. The Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) performs best in the Average Flow Category, with median preservation risk ranks and an interquartile range below the 2008-2024 defined threshold. The Enhanced Coordination, Maximum Operational Flexibility, and Representative Preferred Alternatives perform similarly to one another, with median preservation risk ranks at or below the threshold and interquartile ranges that are mostly below the threshold. As the modeling enters the Critically Dry Flow Category, performance shifts to the CCS Comparative Baseline and the No Action, Basic Coordination, and Supply Driven Alternatives maintaining interquartile ranges below the threshold. Preservation risk ranks across all alternatives are above the threshold, with the Representative Preferred Alternative exhibiting the highest median. Large boxes on the plot represent more uncertainty as to how conditions might change, and the larger the section of the box that is above the threshold line, the more resources that are being exposed to risks they have not faced since Lake Mead was filled.

For all hydrology except the Critically Dry Flow Category, the Maximum Operational Flexibility Alternative and Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) perform similarly with a median preservation risk around, or just above, the historical threshold. The Maximum Operational Flexibility Alternative appears to have slightly less variability with a smaller interquartile range, though a larger percentage of the range is above the historical threshold. The Enhanced Coordination Alternative has a slightly larger median preservation risk rank but a smaller interquartile range, suggesting less variability in results but more certainty of the preservation risk exceeding historical conditions. Under the driest conditions, all alternatives have a moderately strong chance of exceeding the historical preservation risk conditions.

At Lake Mead, the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) results in the least variability and most values below the threshold. The Representative Preferred Alternative performs generally in the middle of the alternatives, suggesting that preservation risk ranks will exceed historical conditions over the planned length of the decision.

Figure TA 12-7
Water Year Maximum Paleontological Preservation Risk at Lake Mead

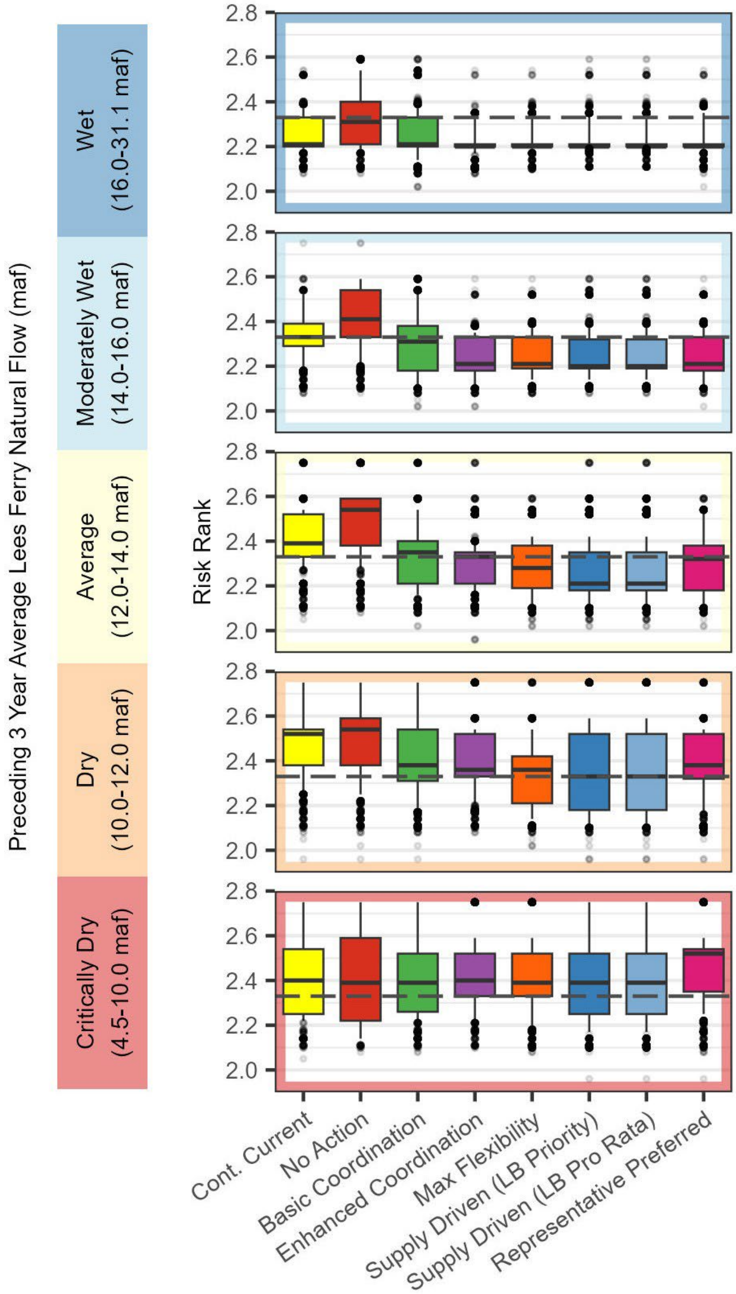
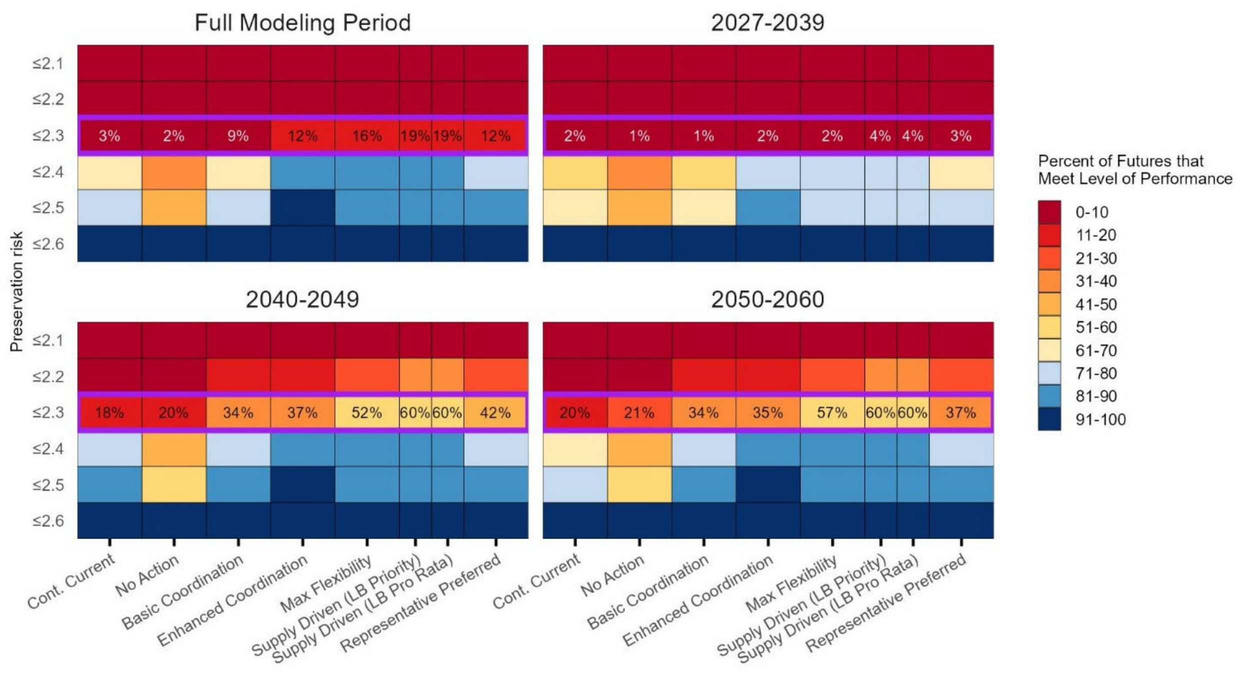


Figure TA 12-8, below, depicts the performance of each alternative with respect to keeping paleontological preservation risk ranks at Lake Mead below the historically derived threshold in at least 90 percent of months. This is the same threshold as what was used in **Figure TA 12-7**. The figure is broken into four heat maps, each showing a different time period during the analysis. The top left heat map shows the full modeling period from 2027 through 2060, and the remaining three panels show subperiods. Rows of the heat map show different preservation risk ranks, with higher rows corresponding to lower (more challenging) ranks. The highlighted row captures the percentage of futures that an alternative achieves a rank of 2.3 in 90 percent of the months.

The Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) is the most robust at achieving a risk rank of 2.3 in 90 percent of months over the full modeling period, doing so in 19 percent of the futures. The Maximum Operational Flexibility Alternative performs similarly to the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches), achieving a risk rank of 2.3 in 16 percent of futures. The No Action Alternative and CCS Comparative Baseline are the least robust and perform identically, succeeding in 2 percent and 3 percent of futures, respectively; the Representative Preferred Alternative and Enhanced Coordination Alternative perform the same (12 percent successful futures). In lower rows of the heat map, the Enhanced Coordination Alternative achieves 91–100 percent robustness by 2.5. The CCS Comparative Baseline and all other alternatives achieve 91–100 percent robustness at 2.6.

Figure TA 12-8
Paleontological Resources in Lake Mead NRA: Robustness.
Percentage of Futures in Which Monthly Preservation Risk Stays Below the Value Specified in Each Row in at Least 90 Percent of Months



Robustness of the alternatives does not immediately improve when analyzing shorter modeling periods. In the 2027–2039 period, robustness of the CCS Comparative Baseline and all action alternatives drop; the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) drops more than 10 percent, from 19 percent in the full modeling period to 4 percent in the 2027–2039 decadal subperiod. Given the planned length of the decision, it is notable that the Representative Preferred Alternative is robust in only 3 percent of futures between 2027 and 2039, suggesting that reservoir fluctuations in Lake Mead will result in exposure, erosion, and degradation of paleontological resources at rates greater than historically observed.

Robustness quickly improves in the 2040–2049 and 2050–2060 subperiods. The Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) is the most robust in 2040–2049, with 60 percent of futures achieving a risk rank of 2.3 in 90 percent of months. However, the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) is slower to improve performance in the lower rows; the Enhanced Coordination Alternative reaches 91–100 percent robustness at 2.5. The Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) reaches 91–100 percent robustness at 2.6.

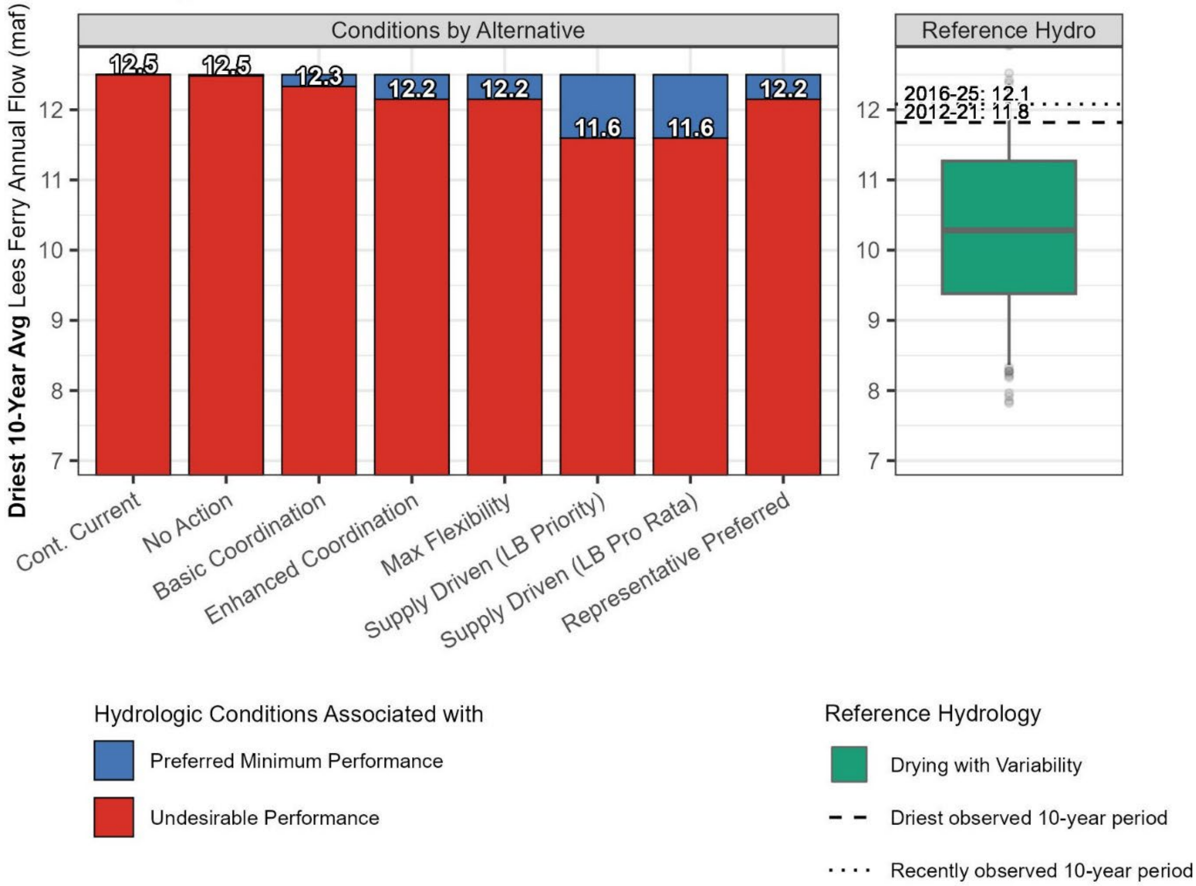
In the 2050–2060 subperiod, the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) continues to perform best with respect to the historically derived threshold. However, the Enhanced Coordination Alternative reaches 91–100 percent robustness at 2.5. At the historically derived threshold, the Maximum Operational Flexibility Alternative is more robust than the Enhanced Coordination Alternative (57 percent and 35 percent, respectively). However, the Enhanced Coordination Alternative is faster to achieve 91–100 percent robustness. Overall, the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) is the most robust alternative at Lake Mead in the 2050–2060 subperiod, achieving 90 percent of months where the historically derived threshold is met in 60 percent of futures. The Representative Preferred Alternative continues to perform generally in the middle of the alternatives at Lake Mead.

Figure TA 12-9, below, looks at flow conditions that could cause the preservation risk rank at Lake Mead to exceed the historically derived threshold in more than 10 percent of months of the 34-year modeling horizon. The driest 10-year average Lees Ferry natural flow was identified as a good predictor of undesirable performance; this is shown in the reference hydrology panel along with the driest and recently observed 10-year period.

Paleontological resources are the most vulnerable to risk under the CCS Comparative Baseline and No Action Alternative. Undesirable performance occurs at 12.5 maf; nearly 100 percent of the reference hydrology traces include average flows of 12.5 maf or lower. These two scenarios are vulnerable to conditions that have already occurred; average flows of 11.8 maf occurred during the driest observed 10-year period. The Basic Coordination Alternative and Enhanced Coordination Alternative are vulnerable to increased risk to paleontology sites at flows of 12.3 maf and 12.2 maf, respectively. Under all alternatives where the undesirable performance is greater than 12.1 maf, vulnerability is nearly certain.

The Maximum Operational Flexibility and Representative Preferred Alternatives result in undesirable performance if the future includes a driest 10-year flow of 12.2 maf, which is the greater than the 2012–2021 driest observed flow. Under the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches), paleontological resources become vulnerable to risk at flows of 11.6 maf. Approximately 75 percent of reference hydrology traces are drier than 11.6 maf, so the vulnerability is considered high. It is notable that under the Representative Preferred Alternative, paleontological resources in Lake Mead would be vulnerable to exposure, erosion, and degradation when flows are 12.2 maf or less.

Figure TA 12-9
Paleontological Resources in Lake Mead NRA: Vulnerability.
Conditions that Could Cause Risk to Paleontological Sites in Lake Mead Exceeding Historical Benchmark More than 10 Percent of Months



Summary Comparison of Alternatives

Lake Powell and Lake Mead

Continuous inundation preserves paleontological resources better than repeated exposure to waves and wet-dry cycles. Changes in lake elevations that may expose previously inundated paleontological resources are the biggest concern; the Paleontological Preservation Risk Model uses lake elevations to establish risk. For Lake Powell, the Enhanced Coordination Alternative performs best with regard to meeting the paleontological preservation risk rank threshold in all hydrologic conditions except the Critically Dry Flow Category; this alternative is followed by the Maximum Operational Flexibility Alternative. Both alternatives exhibit median risk ranks that are at or below the threshold. The Basic Coordination Alternative is the least effective action alternative with regard to meeting the paleontological preservation risk threshold. This alternative becomes successful at the Moderately Wet Flow Category but consistently exceeds the threshold at the Average Flow Category and drier. The No Action Alternative and CCS Comparative Baseline perform similarly to the Basic Coordination Alternative.

For Lake Mead, the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) and Maximum Operational Flexibility Alternative perform similarly and produce median preservation risk rank around, or just above, the historically derived threshold in all hydrologic conditions except the Critically Dry Flow Category. All alternatives exceed historical preservation risk conditions under the Critically Dry Flow Category.

For both Lake Powell and Lake Mead, the Representative Preferred Alternative generally performs somewhere in the middle of the action alternatives, never outperforming all alternatives in terms of paleontological resource risk reduction. Given the length of the planned decision, it is notable that paleontological preservation risk will likely be heightened under the Representative Preferred Alternative, as more resources will become exposed and eroded due to fluctuating reservoir levels and flows.

Under the Maximum Operational Flexibility Alternative, the paleontological preservation risk rank would be maintained at or below the threshold of significance for the most amount of time across both reservoirs. Paleontological resources that are inundated by lake elevations would not be exposed to erosion, degradation, and the repeated cycles of inundation and exposure and wave action. The Maximum Operational Flexibility Alternative would be a balanced approach minimizing preservation risk. The Enhanced Coordination Alternative would also maintain paleontological preservation risk rank in the reservoirs, but not as consistently as under the Maximum Operational Flexibility Alternative.

TA 12.2.3 Issue 2: How will altered sediment transport, including both fluvial and aeolian deposition patterns, affect the preservation and stability of paleontological resources?

The preservation and stability of paleontological resources along the Colorado River corridor are closely tied to sediment dynamics, particularly the deposition and redistribution of fine sediments through fluvial and aeolian processes. Sediment burial helps protect surface-exposed resources from erosion, weathering, and human disturbance, while changes in the magnitude or timing of sediment delivery may either enhance or degrade preservation conditions. However, increased exposure of sandbars and sediment surfaces typically heightens the risk of erosion, weathering, and loss of fossil integrity, while sediment deposition and rapid burial may provide temporary protection from degradation. Frequent fluctuations in the water level that alternately expose and inundate sediments are generally detrimental to long-term preservation.

Fluvial Sediment Transport

Figure TA 12-10 depicts the performance of each alternative with respect to the fraction of total sand mass transported by sandbar-forming flows, defined as releases greater than 37,000 cubic feet per second (cfs), over the 34-year modeling horizon. As detailed in **TA 5**, Geomorphology and Sediment, HFE releases represent Reclamation's primary tool for managing the limited sediment resources and maintaining or increasing sandbar size. These controlled floods, which range from approximately 31,500 cfs to over 37,000 cfs, are the only mechanism capable of producing widespread sandbar building (Hazel et al. 2022; Salter et al. 2025). Sandbars erode between HFE releases (Hazel et al. 2022), with the highest rates immediately after a flood (when bars have the most sediment available for erosion) and decreasing with time (Grams et al. 2010). Steadier flows erode bars at a lower rate than fluctuating flows (Wright et al. 2008).

Figure TA 12-10
Sand-Load Index: Robustness.
Percentage of Futures in Which the Fraction of Sand Mass Transported Above 37,000 cfs is the Value Specified in Each Row

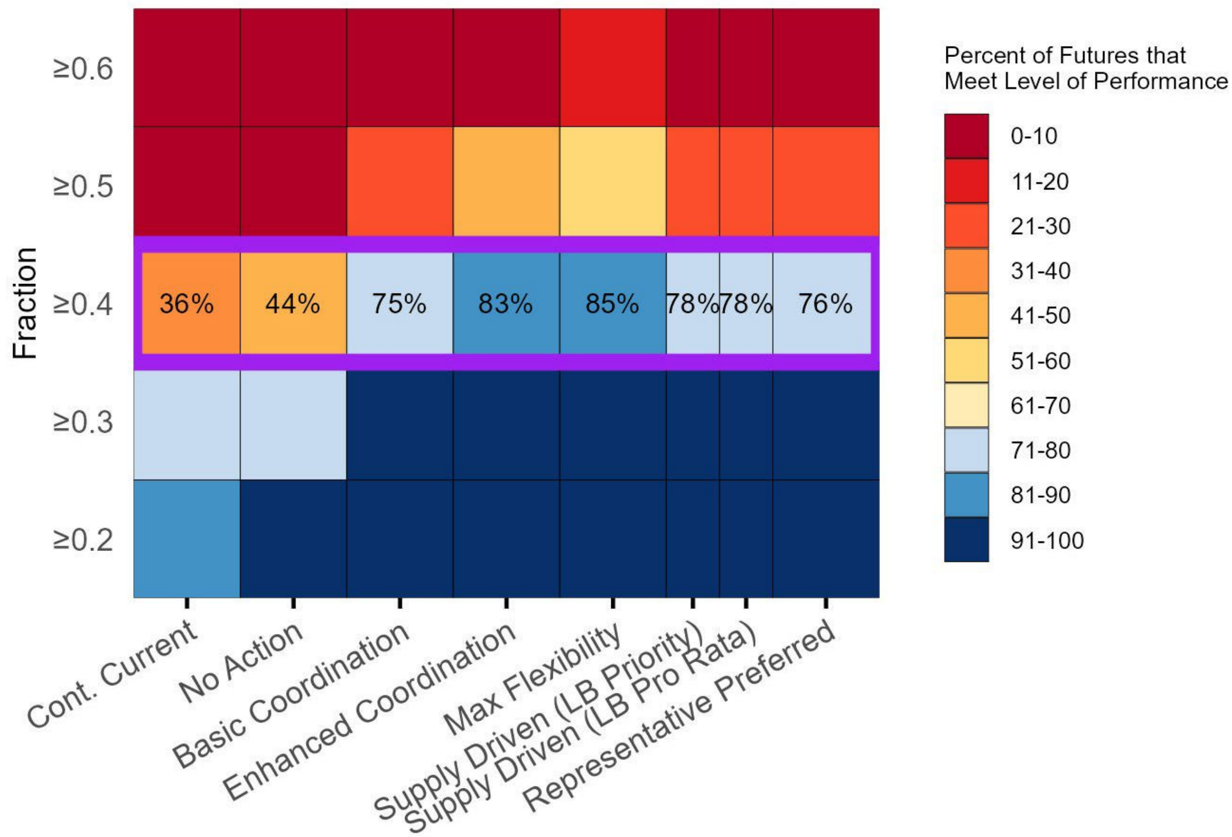


Figure TA 12-10 evaluates how robustly each alternative supports sandbar formation by showing the percentage of futures in which at least 40 percent of total sand mass is transported during sandbar-forming flows. This 40 percent threshold was selected as an indicator of conditions likely to support adequate sand deposition to retain sandbars. Due to modeling constraints, this figure only depicts robustness for the entire modeling period and does not include decadal subperiods.

The Enhanced Coordination and Maximum Operational Flexibility Alternatives exhibit the highest robustness; each achieves successful outcomes—defined as meeting or exceeding the 40 percent threshold—in 83 percent and 85 percent of futures, respectively. Under these alternatives, sediment transport dynamics would generally support sandbar deposition at satisfactory levels, which would indirectly result in desirable levels of sand for fossil reburial.

The Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) meets the threshold in 78 percent of futures, while the Representative Preferred and Basic Coordination Alternatives perform moderately lower at 76 percent and 75 percent, respectively. These three alternatives perform similarly to the Enhanced Coordination and Maximum Operational Flexibility Alternatives because their robustness is within 10 percent of each other, and all five action alternatives reach 91-100 percent robustness within one row of the heatmap. It is notable that the Representative

Preferred Alternative meets the threshold similarly to the highest performing alternative, indicating that sandbar building would continue to occur at rates beneficial to fossil reburial.

Under both the No Action Alternative and the CCS Comparative Baseline, fewer than half of futures meet the 40 percent sandbar-forming flow threshold, with the CCS Comparative Baseline exhibiting the lowest success rate of all alternatives. These outcomes indicate that sand would be transported at rates less favorable for sandbar building and that fossils would be at greater risk of exposure during the erosion of sandbars and less frequently buried during sandbar-building events under the No Action Alternative.

Aeolian Sediment Transport

As discussed above in **Section TA 12.2.1**, Methodology, the aeolian transport model looks at favorable conditions for wind-borne sand to be present to protect paleontological resources over long periods of time using projected vegetation cover and exposed sand area or sandbar volume (Kelley et al. 2026). The vegetation and sandbar volume modeling used is from the Marble Canyon sub-reach from Lees Ferry to the Little Colorado River. The exposed sand modeling was conducted for the portion of the river from Lees Ferry to Bright Angel Creek. But the general conclusions are pertinent to the entire river.

The results of the annual vegetation cover modeling are presented in **Section TA 9**, Vegetation Including Special Status Species. Overall, less vegetation is better for aeolian sand transport because it leaves sand exposed to be picked up by the wind. As discussed in **Section TA 9.2.2** and seen in **Figure TA 9-13**, for all modeled scenarios under the wet and moderately wet conditions, there would be less vegetation cover (below observed conditions) from higher water levels and longer HFEs. As conditions grow drier, water flows diminish, HFEs are shorter, and vegetation cover increases (see **Figure TA 9-13**).

For the Average Flow Category, the median for the CCS Comparative Baseline, the No Action Alternative and all action alternatives (including the Representative Preferred Alternative) is at or just below the modeled historical conditions (i.e., the 2007 Interim Guidelines period [WY 2008–2025]) and the interquartile ranges are relatively small. This indicates that the annual total vegetation may be similar to historical conditions under average flows. Conversely, under the dry and critically dry conditions, annual total vegetation cover increases and differentiation between alternatives can be seen. For the Critically Dry Flow Category, the medians and interquartile ranges are above the modeled historical conditions (dashed line) for all sub-reaches and all alternatives except the interquartile range for the CCS Comparative Baseline, which drops just below the dashed line (see **Figure TA 9-14** in **TA 9**). This indicates that there may be more annual total vegetation cover, especially under critically dry flows.

The results of the sandbar volume modeling are presented in **TA 5**, Geomorphology and Sediment. As discussed in **TA 5**, for an HFE to be triggered, enough sand needs to be available in Marble Canyon and enough water needs to be available in Lake Powell (as measured by water level), with both the required amounts of sand and water being dependent on the selected HFE duration. Additionally, HFE releases can only be implemented when Lake Powell water levels are 3,500 feet, with sandbar deposition occurring most rapidly during the first 4 days of an HFE event. Lastly, sandbar volume modeling uses the assumption that HFEs are implemented as often as possible (see **Section TA 5.2.1**, Modeling Criteria and Assumptions). For the aeolian transport model, increased exposed sandbar volume (or the amount of "useable" sand) means more sand is available to protect paleontological resources. In general, as conditions get drier and the amount of water flowing through the river decreases, exposed sandbar volume increases (see **Section TA 5.2.4**, Issue 4: Sandbar Volume, in **TA 5**, Geomorphology and Sediment). Differences in performance among the alternatives also increase as hydrological conditions become drier, with the Enhanced Coordination and Maximum Operational Flexibility Alternatives performing the best for the Critically Dry Flow Category (see **Figure TA 5-12** in **TA 5.2.5**).

Figure TA 12-11 shows the results of the water year average of exposed sand area modeling, with the 90th percentile and median (50th percentile) of modeled sand areas depicted as the two dashed lines. As with exposed sandbar volume, increased exposed sand area is beneficial for the aeolian transport of sand to protect paleontological resources. In the Average Flow Category, the median exposed sand area is around the 90th percentile (upper dashed line) and the median (50th percentile, lower dashed line) of modeled sand area (in million square meters). As conditions become drier, all modeled scenarios perform similarly with the forecasted median exposed sand area above the observed median with the Enhanced Coordination Alternative having a slighter higher median than the action alternatives. In the Critically Dry Flow Category, the Maximum Operational Flexibility Alternative exhibits the most variability with the greatest interquartile range. The Representative Preferred Alternative generally performs in the middle of the action alternatives, indicating that the exposed sand area will be conducive to the protection of paleontological resources through aeolian transport.

Figure TA 12-12 shows the results of the aeolian sand modeling, in which the percentage of futures meet one of two criteria: either the annual sand volume is greater than the median observed sand volume over the last 20 years and the vegetation cover area is less than the median observed area over the last 20 years, or the sandbar volume is greater than 1.5 times the initial condition. The highlighted row shows when those conditions are met at least 1 out of every 3 years, which is the optimal time frame for enough sand to be available for aeolian transport, based on previous studies.

Over the full modeling period, the Enhanced Coordination and the Maximum Operational Flexibility Alternatives are the most robust; they meet the desired conditions of at least 1 out of every 3 years in 19 percent and 18 percent of futures, respectively, followed by the No Action Alternative only in 14 percent of futures. The Basic Coordination Alternative meets the preferred minimum of performance in only 9 percent of futures, with the Representative Preferred Alternative meeting it in only 6 percent of futures. The Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) is the least robust, meeting the desired conditions in only 3 percent of futures. If the year interval is lengthened (that is, to 1 out of 4, 5, or 6 years), the models perform in a similar overall pattern; the Enhanced Coordination and the Maximum Operational Flexibility Alternatives perform the best.

Figure TA 12-11
Water Year Average of Exposed Sand Area

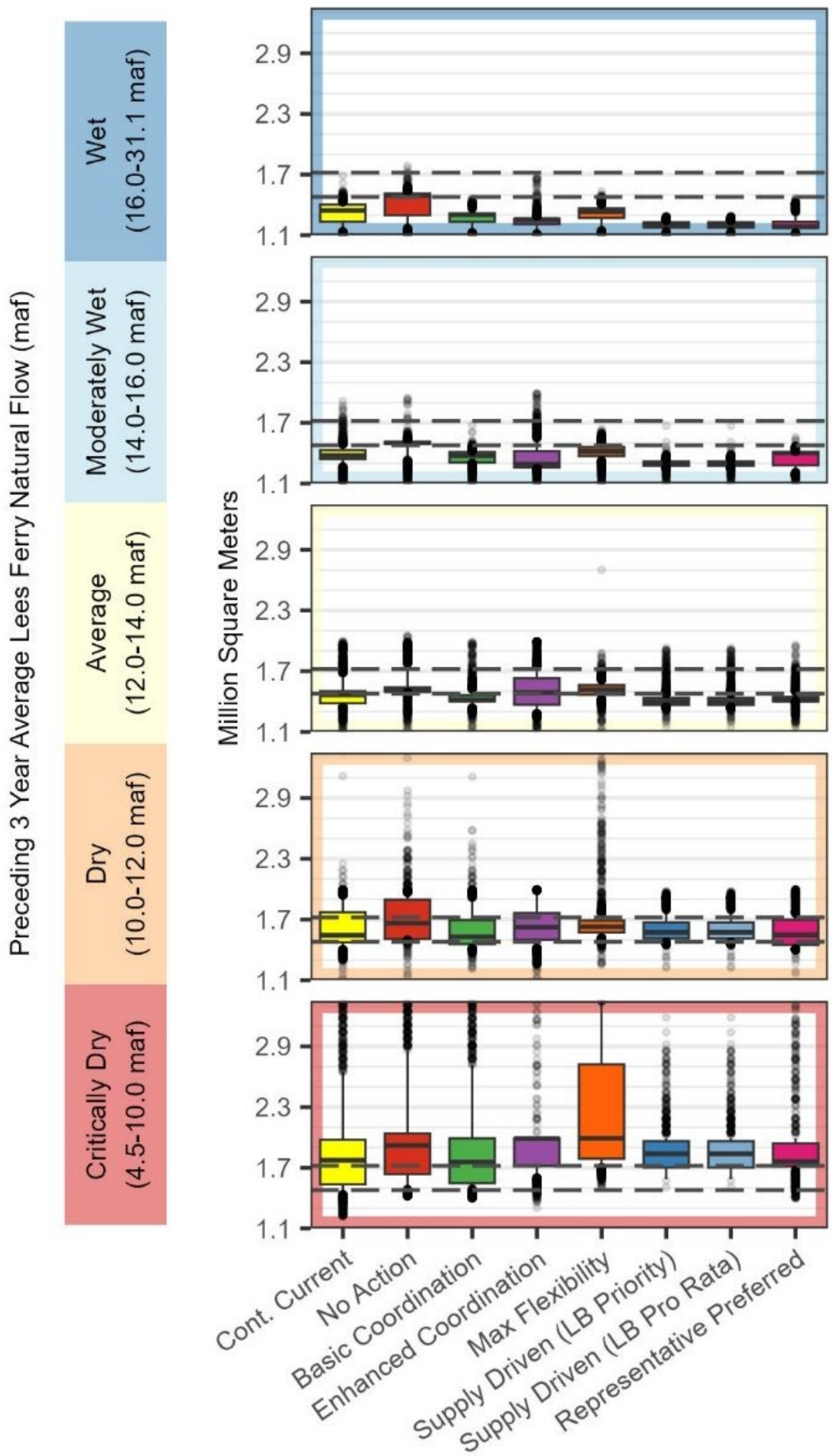
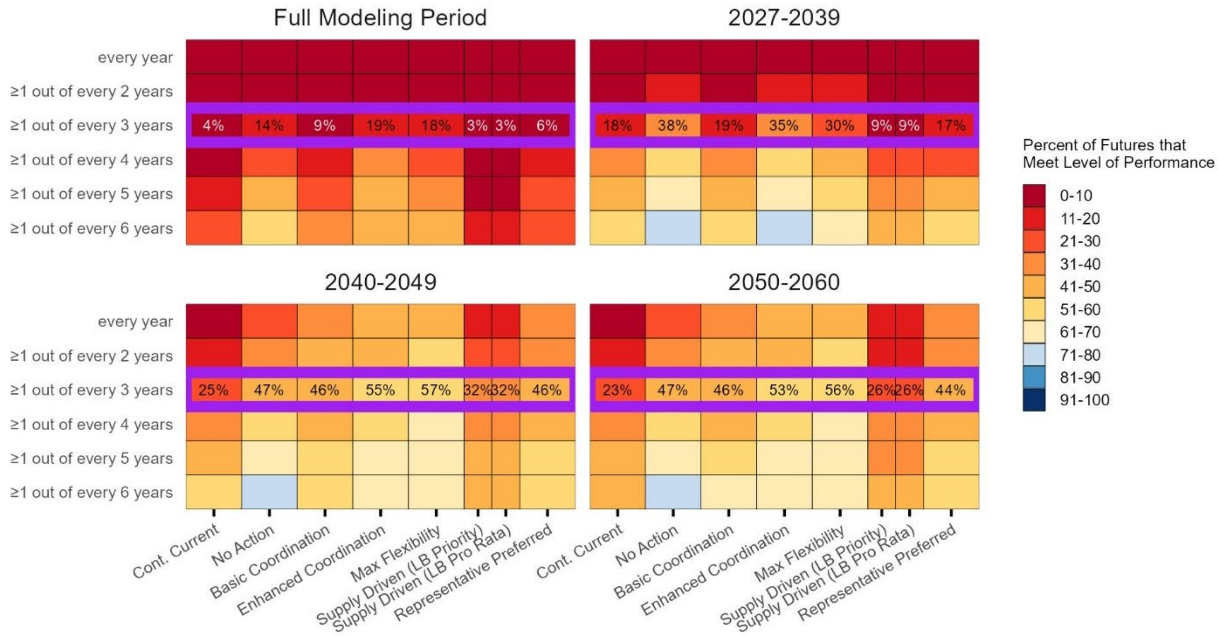


Figure TA 12-12
Multi-modal Aeolian Transport Condition: Robustness.
Percentage of Futures in Which Annual Sand Area Is >50th Percentile and Vegetation Cover Is <50th Percentile, or Sandbar Volume Is >1.5 Times the Initial Condition in the Frequency Specified in Each Row



It is notable that the Representative Preferred Alternative meets the desired conditions in 17 percent of futures between 2027 and 2039, indicating that the conditions required for aeolian transport will not occur frequently, exposing paleontological resources to erosion and other weathering mechanisms.

When results are split over intervals from 2027–2039, 2040–2049, and 2050–2060, the percentage of futures meeting the desired conditions increase for both the Enhanced Coordination and the Maximum Operational Flexibility Alternatives from 35 percent to 55 percent and 53 percent and from 30 percent to 57 percent and 56 percent, respectively. These results seem to indicate an increase in acceptability over time, which may correlate to increased available sand over time; however, the perceived increase is driven by an increase in sandbar volume over time in the modeling, with the understanding that HFEs would continue as planned. In reality, the decision to conduct HFEs depends on annual review.

Summary Comparison of Alternatives

Fossils and other paleontological resources that become exposed to oxygen, wind, and erosion are vulnerable to degradation. Sediment transport, by both aeolian and fluvial processes, can better preserve paleontological resources through burial. Changes in river flows and HFEs can affect the amount of sediment available for transport and indirectly impact the stability and preservation of fossils and other paleontological resources.

Based on the modeling, the Enhanced Coordination Alternative and Maximum Operational Flexibility Alternative were the most robust for sand transport during HFEs. Under these alternatives, the rate of sand transport would generally support sandbar building and indirectly contribute to the burial and preservation of paleontological resources. In contrast, the No Action Alternative was the least robust, and HFEs would not support sandbar building in more than 44 percent of futures.

The Enhanced Coordination Alternative and Maximum Operational Flexibility Alternative were also the most robust for aeolian transport of sediment. Although the robustness modeling results showed only 19 and 18 percent of successful futures for these alternatives, respectively, the Basic Coordination Alternative and Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) produced values of 9 percent or lower.

The Representative Preferred Alternative generally performs in the middle of the action alternatives, never outperforming the best alternative with regard to paleontological resources. This means that paleontological resources will be vulnerable to altered fluvial and aeolian sediment transport, particularly between 2027 and 2039. Paleontological resources are likely to be exposed rather than buried, and may be degraded by multiple weathering mechanisms over time.

The river corridor, from below Hoover Dam to the SIB, is not well mapped by PFYC. Classifications in the corridor are mostly PFYC W (water). While possible, the presence or impacts on scientifically important vertebrate fossils are not anticipated within the river corridor when compared with the potential for known or undiscovered fossils in the reservoirs. The Enhanced Coordination Alternative and Maximum Operational Flexibility Alternative are the most robust alternatives with regard to sediment transport in the river corridor. Sediment transport would indirectly preserve and stabilize the known and unknown fossil localities.

TA 12.2.4 Issue 3: How will adjustments to dam operations and water levels alter human access to newly exposed fossil sites, and what are the potential risks of increased disturbance, unauthorized collection, and recreational impacts on paleontological resources?

The Paleontological Preservation Risk Model does not include the indirect impacts of human disturbance. However, the model does correlate with lake elevations at Lake Powell and Lake Mead. As lake elevations drop, more of the reservoir becomes accessible to visitors, particularly in flatter areas that are easy to access. The longer amount of time lake elevations remain low, the more vulnerable paleontological resources become to increased rates of disturbance, unauthorized collection, and recreational impacts. The DMDU analysis used for lake elevations in **TA 3**, Hydrologic Resources, is used in conjunction with the paleontological preservation risk to conduct the analysis of indirect impacts on paleontological resources from the alternatives.

Lake Powell

This section presents a comparison of the No Action Alternative, CCS Comparative Baseline, and action alternatives with respect to increased disturbance of, unauthorized collection of, and recreational impacts on paleontological resources at Lake Powell. For a more detailed analysis of recreation at Lake Powell, please refer to **TA 14**, Recreation. For a more detailed analysis of hydrologic conditions at Lake Powell, please refer to **TA 3**, Hydrologic Resources.

The alternatives perform similarly with respect to maintaining lake elevations and achieving desirable paleontological preservation risk ranks. The Maximum Operational Flexibility Alternative and Enhanced Coordination Alternative are the most robust at staying above 3,500-foot elevation in 100 percent of months over the full modeling period, doing so in 86 percent and 74 percent of futures, respectively. This result is similar to the robustness of both alternatives with regard to achieving the historically derived preservation risk threshold in 90 percent of months.

The No Action Alternative is the least robust at maintaining 3,500-foot elevation in 100 percent of months, doing so in 4 percent of futures over the full modeling period. The No Action Alternative is only 61–70 percent robust at maintaining this elevation in 60 percent of months. The CCS Comparative Baseline, Basic Coordination Alternative, and Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) perform similarly, maintaining the 3,500-foot elevation in 100 percent of months in 18 percent, 13 percent, and 18 percent of futures, respectively.

The Representative Preferred Alternative meets this robustness criteria in 28 percent of modeled futures in the full modeling period. Based on the planned length of this alternative, it is important to note that it meets the preferred minimum performance level in 49 percent of futures between 2027 and 2039. The Representative Preferred Alternative is much less robust than the Maximum Flexibility and Enhanced Coordination Alternatives, but it is much more robust than all other alternatives and the CCS Comparative Baseline.

Alternatives that keep Lake Powell at or above 3,500 feet more often will keep most sites below that level underwater (and protected) more of the time. Therefore, the risk of human disturbance would be for resources above 3,500 feet. The preservation risk rank's historically derived threshold is achieved at approximately 3,500-foot elevation at Lake Powell. Under the Maximum Operational Flexibility Alternative, elevations at Lake Powell would be most consistently at or above 3,500 feet, which would result in the inundation of the most paleontological resources and the least amount of shoreline expansion for visitors to access resources.

Lake Mead

This section presents a comparison of the No Action Alternative, CCS Comparative Baseline, and action alternatives with respect to increased disturbance of, unauthorized collection of, and recreational impacts on paleontological resources at Lake Mead. For a more detailed analysis of recreation at Lake Mead, please refer to **TA 14**, Recreation. For a more detailed analysis of hydrologic conditions at Lake Mead, please refer to **TA 3**, Hydrologic Resources.

The alternatives perform similarly with respect to maintaining lake elevations and achieving desirable paleontological preservation risk ranks. The Supply Driven Alternative (LB Pro Rata) and Maximum Operational Flexibility Alternative are similarly robust at keeping Lake Mead elevation above 975 feet in 100 percent of months, doing so in 73 percent and 70 percent of futures, respectively. The Enhanced Coordination Alternative and Supply Driven Alternative (LB Priority) are also similarly robust, maintaining Lake Mead elevation above 975 feet in 65 percent and 61 percent of futures, respectively.

The Representative Preferred Alternative meets this robustness criteria in 50 percent of modeled futures in the full modeling period. Based on the planned length of this alternative it is important to note that it meets the preferred minimum performance level in 66 percent of futures between 2027 and 2039.

The No Action Alternative is the least robust, keeping Lake Mead elevation above 975 feet in 100 percent of months in 21 percent of futures over the full modeling period. Robustness of the CCS Comparative Baseline is 38 percent; robustness of the Basic Coordination Alternative is 50 percent.

Summary Comparison of Alternatives

Lake Powell and Lake Mead

Changes in dam operations that lower reservoir levels can expand the extent of exposed shorelines and channel margins, increasing human access both by land and by small watercraft. Recreational activities such as off-highway vehicle use, hiking, camping, and boating at and around the reservoirs can inadvertently disturb fragile paleontological materials through trampling, erosion from trail formation, or sediment displacement. Additionally, unauthorized fossil collection, either intentional or opportunistic, may increase as new sites become visible and accessible to the public. Once displaced or removed, contextual information critical for scientific study and resource management may be lost.

Increased public presence also raises the likelihood of secondary impacts, such as looting, vandalism, or inadvertent exposure through surface collection. These impacts are particularly concerning in areas lacking monitoring or signage that would otherwise deter unauthorized activities. Conversely, rapid reburial of exposed sites during subsequent water level rises may offer temporary protection from ongoing disturbance, although repeated exposure and burial cycles can weaken fossil integrity over time.

Under the Maximum Operational Flexibility Alternative, the paleontological preservation risk rank would be maintained at or near the historically derived threshold in both Lake Powell and Lake Mead. Additionally, critical lake elevations would be maintained at 3,500 feet in Lake Powell and 975 feet in Lake Mead in 87 percent and 80 percent of futures, respectively. The operations proposed under the Maximum Operational Flexibility Alternative would result in the least amount of time paleontological resources below critical elevations are exposed to human disturbance and associated impacts.

Under the Representative Preferred Alternative, critical lake elevations would be maintained at 3,500 feet in Lake Powell and 975 feet in Lake Mead 28 percent and 50 percent of futures, respectively. The operations proposed under the Representative Preferred Alternative only result in better conditions for the preservation of paleontological resources when compared with the CCS Comparative Baseline, No Action Alternative, and the Basic Coordination Alternative in both reservoirs.

The Basic Coordination Alternative would result in greater stretches of time where the paleontological preservation risk threshold is exceeded, and greater stretches of time where lake elevations drop below critical thresholds. This would result in increased accessibility to vulnerable paleontological sites, and more opportunities for human disturbance.

Management challenges include identifying and monitoring newly exposed areas in real time, implementing site protection measures (such as signage, education, and enforcement), and coordinating with agencies and research institutions to document and recover significant finds before they are lost. Adaptive management strategies—such as targeted public outreach, remote sensing, and rapid site assessment protocols—could mitigate potential damage while accommodating necessary operational changes to the dams.

Statistical Summary Tables

Table TA 12-4
Water Year Maximum Paleontological Preservation Risk at Lake Powell

Alternative	Flow Category (maf)	Max	90th percentile	75th percentile	Median	25th percentile	10th percentile	Min
CCS Comparative Baseline	16.0–31.11	3.17	**2.85**	**2.45**	**2.44**	**2.39**	**2.39**	**2.26**
CCS Comparative Baseline	14.0–16.0	3.32	3.04	2.93	**2.85**	**2.44**	**2.39**	**2.26**
CCS Comparative Baseline	12.0–14.0	3.71	3.25	3.17	2.93	**2.91**	**2.45**	**2.26**
CCS Comparative Baseline	10.0–12.0	3.71	3.32	3.32	3.17	3.04	**2.92**	**2.35**
CCS Comparative Baseline	4.46–10.0	3.71	3.71	3.49	3.32	3.17	3.04	**2.35**
No Action	16.0–31.11	3.17	**2.45**	**2.44**	**2.39**	**2.39**	**2.39**	**2.26**
No Action	14.0–16.0	3.41	3.04	2.93	**2.45**	**2.44**	**2.39**	**2.26**
No Action	12.0–14.0	3.71	3.32	3.25	2.93	**2.45**	**2.44**	**2.26**
No Action	10.0–12.0	3.71	3.49	3.41	3.32	3.17	**2.85**	**2.35**
No Action	4.46–10.0	3.71	3.71	3.71	3.41	3.32	3.04	**2.35**
Basic Coordination	16.0–31.11	3.04	**2.45**	**2.45**	**2.44**	**2.39**	**2.39**	**2.26**
Basic Coordination	14.0–16.0	3.32	2.93	2.93	**2.45**	**2.45**	**2.39**	**2.26**
Basic Coordination	12.0–14.0	3.71	3.17	3.04	2.93	**2.87**	**2.45**	**2.35**
Basic Coordination	10.0–12.0	3.71	3.41	3.32	3.17	3.04	**2.92**	**2.35**
Basic Coordination	4.46–10.0	3.71	3.71	3.56	3.32	3.17	3.06	**2.87**
Enhanced Coordination	16.0–31.11	2.93	**2.45**	**2.45**	**2.44**	**2.39**	**2.39**	**2.26**
Enhanced Coordination	14.0–16.0	3.17	**2.85**	**2.45**	**2.45**	**2.44**	**2.38**	**2.13**
Enhanced Coordination	12.0–14.0	3.25	2.93	**2.91**	**2.45**	**2.44**	**2.35**	**2.13**
Enhanced Coordination	10.0–12.0	3.32	3.17	2.93	**2.92**	**2.85**	**2.38**	**2.13**
Enhanced Coordination	4.46–10.0	3.71	3.32	3.17	3.06	2.93	**2.87**	**2.13**

Alternative	Flow Category (maf)	Max	90th percentile	75th percentile	Median	25th percentile	10th percentile	Min
Maximum Operational Flexibility	16.0–31.11	2.93	**2.45**	**2.45**	**2.44**	**2.39**	**2.39**	**2.26**
Maximum Operational Flexibility	14.0–16.0	3.17	**2.85**	**2.45**	**2.45**	**2.44**	**2.38**	**2.26**
Maximum Operational Flexibility	12.0–14.0	3.17	2.93	2.93	**2.85**	**2.45**	**2.38**	**2.27**
Maximum Operational Flexibility	10.0–12.0	3.17	3.17	2.93	2.93	**2.91**	**2.85**	**2.35**
Maximum Operational Flexibility	4.46–10.0	3.71	3.17	3.17	3.06	3.04	**2.92**	**2.35**
Supply Driven (LB Priority)	16.0–31.11	3.17	2.93	**2.45**	**2.45**	**2.44**	**2.39**	**2.26**
Supply Driven (LB Priority)	14.0–16.0	3.32	3.17	2.93	2.93	**2.45**	**2.44**	**2.26**
Supply Driven (LB Priority)	12.0–14.0	3.41	3.25	3.17	2.93	2.93	**2.85**	**2.35**
Supply Driven (LB Priority)	10.0–12.0	3.49	3.32	3.25	3.17	3.04	**2.92**	**2.38**
Supply Driven (LB Priority)	4.46–10.0	3.71	3.49	3.41	3.32	3.17	3.06	**2.87**
Supply Driven (LB Pro Rata)	16.0–31.11	3.17	2.93	**2.45**	**2.45**	**2.44**	**2.39**	**2.26**
Supply Driven (LB Pro Rata)	14.0–16.0	3.32	3.17	2.93	2.93	**2.45**	**2.44**	**2.26**
Supply Driven (LB Pro Rata)	12.0–14.0	3.41	3.25	3.17	2.93	2.93	**2.85**	**2.35**
Supply Driven (LB Pro Rata)	10.0–12.0	3.49	3.32	3.25	3.17	3.04	**2.92**	**2.38**
Supply Driven (LB Pro Rata)	4.46–10.0	3.71	3.49	3.41	3.32	3.17	3.06	**2.87**
Representative Preferred	16.0–31.11	2.93	**2.45**	**2.45**	**2.45**	**2.44**	**2.39**	**2.26**
Representative Preferred	14.0–16.0	3.17	2.93	**2.87**	**2.45**	**2.45**	**2.38**	**2.35**
Representative Preferred	12.0–14.0	3.32	3.17	2.93	2.93	**2.87**	**2.45**	**2.27**
Representative Preferred	10.0–12.0	3.41	3.17	3.17	3.17	2.93	**2.92**	**2.38**
Representative Preferred	4.46–10.0	3.71	3.41	3.32	3.25	3.17	3.04	**2.91**

Note: Ranks in bold are below the historically derived threshold of 2.93. This is the 90th percentile rank from 2008–2024 during LTEMP. Exceeding this value means that a larger percentage of potential resources are exposed to erosion risks than what has happened since Lake Powell was filled.

Table TA 12-5
Water Year Maximum Paleontological Preservation Risk at Lake Mead

Alternative	Flow Category (maf)	Max	90th percentile	75th percentile	Median	25th percentile	10th percentile	Min
CCS Comparative Baseline	16.0–31.11	2.54	2.38	2.33	**2.21**	**2.2**	**2.18**	**2.08**
CCS Comparative Baseline	14.0–16.0	2.75	2.52	2.39	2.33	**2.29**	**2.19**	**2.08**
CCS Comparative Baseline	12.0–14.0	2.75	2.54	2.52	2.39	2.33	**2.28**	**2.05**
CCS Comparative Baseline	10.0–12.0	2.75	2.75	2.54	2.52	2.38	**2.26**	**1.96**
CCS Comparative Baseline	4.46–10.0	2.75	2.75	2.54	2.4	**2.25**	**2.22**	**2.05**
No Action	16.0–31.11	2.59	2.54	2.4	**2.31**	**2.21**	**2.18**	**2.08**
No Action	14.0–16.0	2.75	2.59	2.54	2.41	2.33	**2.21**	**2.08**
No Action	12.0–14.0	2.75	2.59	2.59	2.54	2.38	**2.28**	**2.08**
No Action	10.0–12.0	2.75	2.75	2.59	2.54	2.38	**2.25**	**1.96**
No Action	4.46–10.0	2.75	2.75	2.59	2.39	**2.22**	**2.14**	**2.08**
Basic Coordination	16.0–31.11	2.59	2.38	2.33	**2.21**	**2.2**	**2.14**	**2.02**
Basic Coordination	14.0–16.0	2.59	2.52	2.38	**2.31**	**2.18**	**2.11**	**2.02**
Basic Coordination	12.0–14.0	2.75	2.54	2.4	2.35	**2.21**	**2.16**	**2.02**
Basic Coordination	10.0–12.0	2.75	2.75	2.54	2.38	**2.31**	**2.18**	**1.96**
Basic Coordination	4.46–10.0	2.75	2.75	2.52	2.39	**2.26**	**2.22**	**2.08**
Enhanced Coordination	16.0–31.11	2.54	2.33	**2.21**	**2.2**	**2.2**	**2.17**	**2.08**
Enhanced Coordination	14.0–16.0	2.59	2.35	2.33	**2.21**	**2.18**	**2.11**	**2.02**
Enhanced Coordination	12.0–14.0	2.75	2.39	2.35	2.33	**2.21**	**2.17**	**1.96**
Enhanced Coordination	10.0–12.0	2.75	2.54	2.52	2.36	2.33	**2.21**	**2.08**
Enhanced Coordination	4.46–10.0	2.75	2.59	2.52	2.4	2.33	**2.22**	**2.1**

Alternative	Flow Category (maf)	Max	90th percentile	75th percentile	Median	25th percentile	10th percentile	Min
Maximum Operational Flexibility	16.0–31.11	2.54	2.33	**2.21**	**2.2**	**2.2**	**2.18**	**2.1**
Maximum Operational Flexibility	14.0–16.0	2.59	2.38	2.33	**2.21**	**2.19**	**2.14**	**2.08**
Maximum Operational Flexibility	12.0–14.0	2.59	2.42	2.38	**2.28**	**2.19**	**2.11**	**2.02**
Maximum Operational Flexibility	10.0–12.0	2.75	2.54	2.42	2.36	**2.21**	**2.14**	**2.02**
Maximum Operational Flexibility	4.46–10.0	2.75	2.59	2.52	2.39	2.33	**2.19**	**2.08**
Supply Driven (LB Priority)	16.0–31.11	2.59	2.33	**2.21**	**2.2**	**2.2**	**2.2**	**2.11**
Supply Driven (LB Priority)	14.0–16.0	2.59	2.38	**2.32**	**2.2**	**2.19**	**2.14**	**2.08**
Supply Driven (LB Priority)	12.0–14.0	2.75	2.42	2.35	**2.21**	**2.18**	**2.11**	**2.02**
Supply Driven (LB Priority)	10.0–12.0	2.75	2.59	2.52	2.33	**2.18**	**2.11**	**1.96**
Supply Driven (LB Priority)	4.46–10.0	2.75	2.75	2.52	2.39	**2.25**	**2.17**	**1.96**
Supply Driven (LB Pro Rata)	16.0–31.11	2.59	2.33	**2.21**	**2.2**	**2.2**	**2.2**	**2.11**
Supply Driven (LB Pro Rata)	14.0–16.0	2.59	2.38	**2.32**	**2.2**	**2.19**	**2.14**	**2.08**
Supply Driven (LB Pro Rata)	12.0–14.0	2.75	2.42	2.35	**2.21**	**2.18**	**2.11**	**2.02**
Supply Driven (LB Pro Rata)	10.0–12.0	2.75	2.59	2.52	2.33	**2.18**	**2.11**	**1.96**
Supply Driven (LB Pro Rata)	4.46–10.0	2.75	2.75	2.52	2.39	**2.25**	**2.17**	**1.96**
Representative Preferred	16.0–31.11	2.54	2.35	**2.21**	**2.2**	**2.2**	**2.18**	**2.02**
Representative Preferred	14.0–16.0	2.59	2.38	2.33	**2.21**	**2.18**	**2.11**	**2.02**
Representative Preferred	12.0–14.0	2.59	2.52	2.38	**2.32**	**2.18**	**2.11**	**2.02**
Representative Preferred	10.0–12.0	2.75	2.54	2.52	2.38	**2.32**	**2.17**	**1.96**
Representative Preferred	4.46–10.0	2.75	2.59	2.54	2.52	2.35	**2.25**	**1.96**

Note: Ranks in bold are below the historically derived threshold of 2.33. This is the 90th percentile rank from 2008–2024 during LTEMP. Exceeding this value means that a larger percentage of potential resources are exposed to erosion risks than what has happened since Lake Mead was filled.

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