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
DMDU	decision making under deep uncertainty
GIS	geographic information systems
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
PRPA	Paleontological Resources Preservation Act
PFYC	Potential Fossil Yield Classification
Reclamation	Bureau of Reclamation
SEIS	supplemental environmental impact statement
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 (with some exceptions) any fossilized remains, traces, or imprints of organisms preserved in or on the earth's crust. 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 Department of Interior agencies preserve, manage, and protect paleontological resources on lands administered by Bureau of Reclamation (Reclamation), the National Park Service (NPS), the Bureau of Land Management (BLM) and the U.S. Fish and Wildlife Service and ensure 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 non-renewable resources and once degraded or destroyed can result in the permanent loss of important scientific information about life and environments in Earth's past. Proper management actions can identify how to reduce impacts on paleontological resources leading to their preservation and enhance 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 (SEIS; Reclamation 2024a) do not address paleontological resources as a separate resource concern; the Near-term Colorado River Operations Final SEIS does (Reclamation 2024b). In the 2007 and 2017 analyses, many of the 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 3 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, including a 0.5-mile buffer on either side of the river or canyon rim. 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 in the operational zones are vulnerable to the effects from wave action and other disturbances, and those above the fluctuating pool elevation are at risk for damage and disturbance by visitation.

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 this resource has been submerged by the creation of the reservoirs at Lake Powell and Lake Mead, with minimal data available on the deep-water 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 of Interior agencies to develop plans for inventory and monitoring using scientific principles and expertise. These plans shall emphasize interagency coordination and collaborative efforts, when possible.

Paleontological Resource Assessment Criteria

In recognizing the fact 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, 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 BLM is used by other Department of Interior agencies (BLM-IM-2016-124), is outlined below:

PFYC Class 5—Very High

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.
- Unit is frequently the focus of illegal collecting activities.

PFYC Class 4—High

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

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:

- 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

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.
- Recent aeolian deposits.
- Sediments exhibit significant physical and chemical changes (i.e., diagenetic alteration) that make fossil preservation unlikely.

PFYC Class 1—Very Low

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.

- Geologic units are igneous or metamorphic, excluding air-fall and reworked volcanic ash units.
- Geologic units are Precambrian (e.g., Proterozoic) in age.

PFYC Class U—Unknown

Includes geologic units that cannot receive an informed PFYC assignment. Characteristics of Class U may include:

- 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.
- Geologic units represented on a map are based on lithologic character or basis of origin, but 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.
- Area or geologic unit is poorly-studied or under-studied.
- BLM staff has not yet been able to assess the nature of the geologic unit.

PFYC Class W—Water

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 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 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.

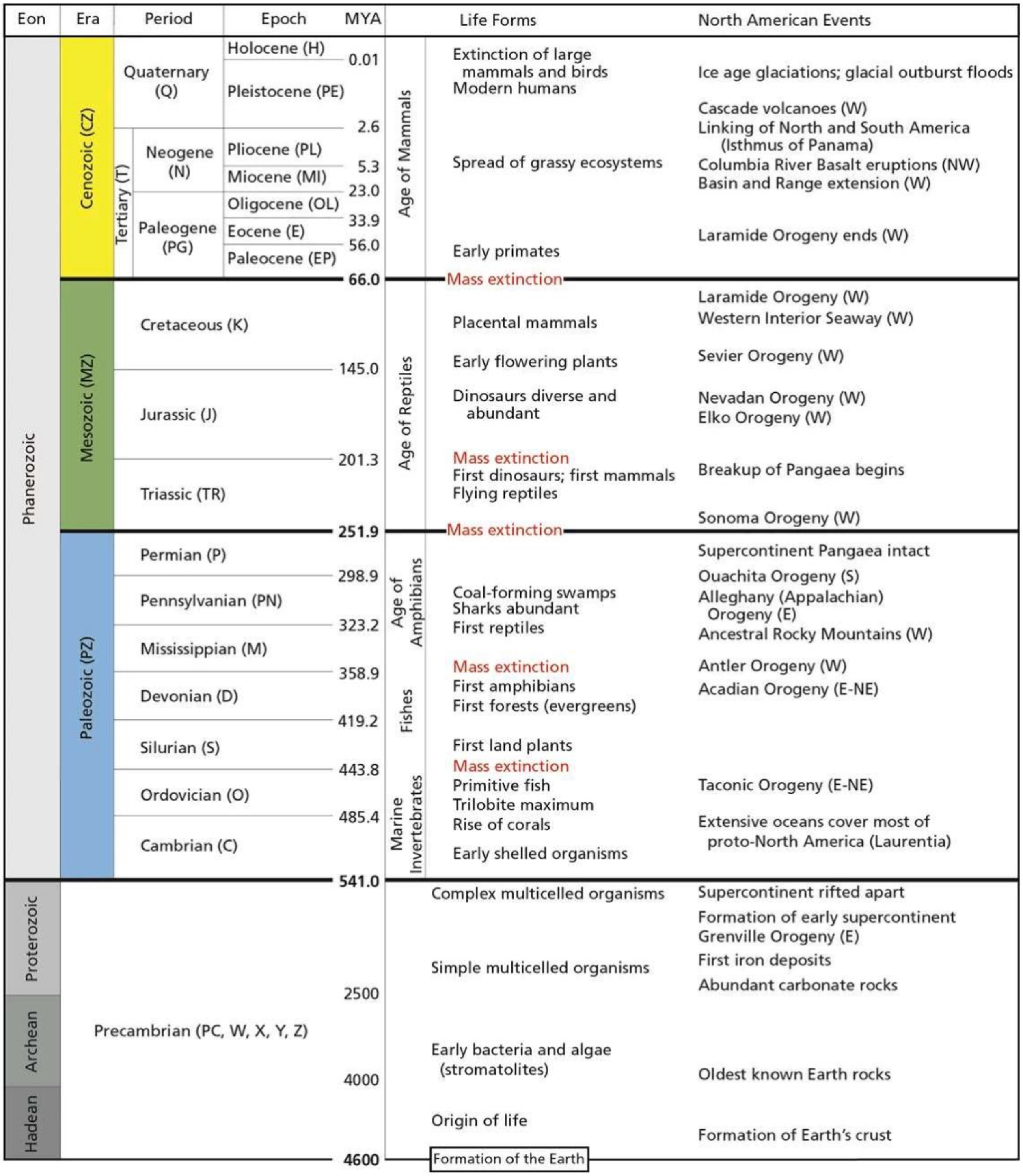
Table TA 12-1
Acres of PFYC within the Study Area

PFYC	Total Acres
1	433,209
2	353,109
3	543,355
4	713,409
5	103,828
U	525,265
W	383,946
Total acres	**3,056,121***

Source: BLM GIS (geographic information systems). 2025.
*PFYC data does not cover the entire study area, especially in the waterbodies and portions of the Colorado River

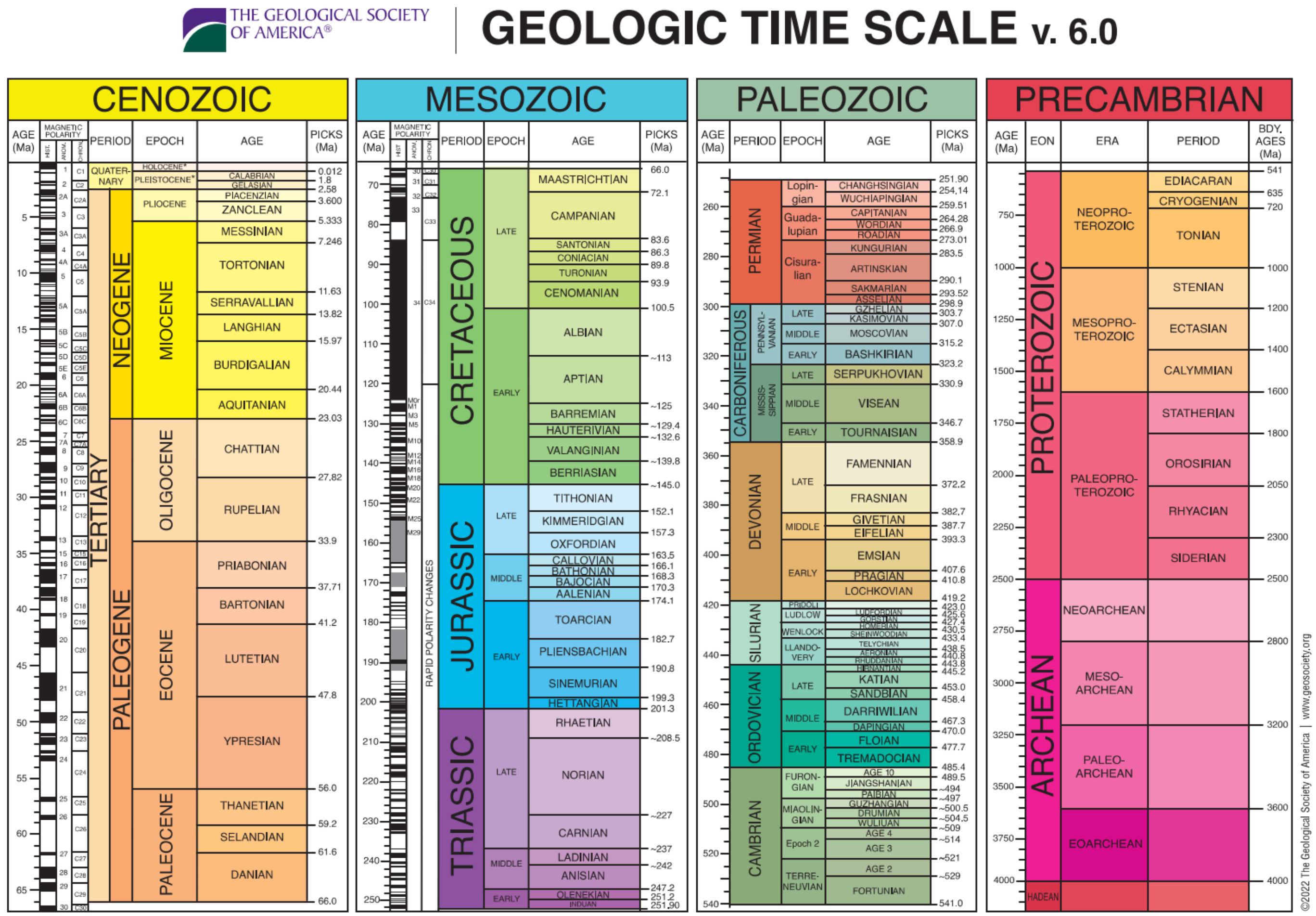
Formation-by-formation summaries of resource type, distribution, and PFYC system classes for all geological units in the study area are summarized in **Table TA 12-2**.

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.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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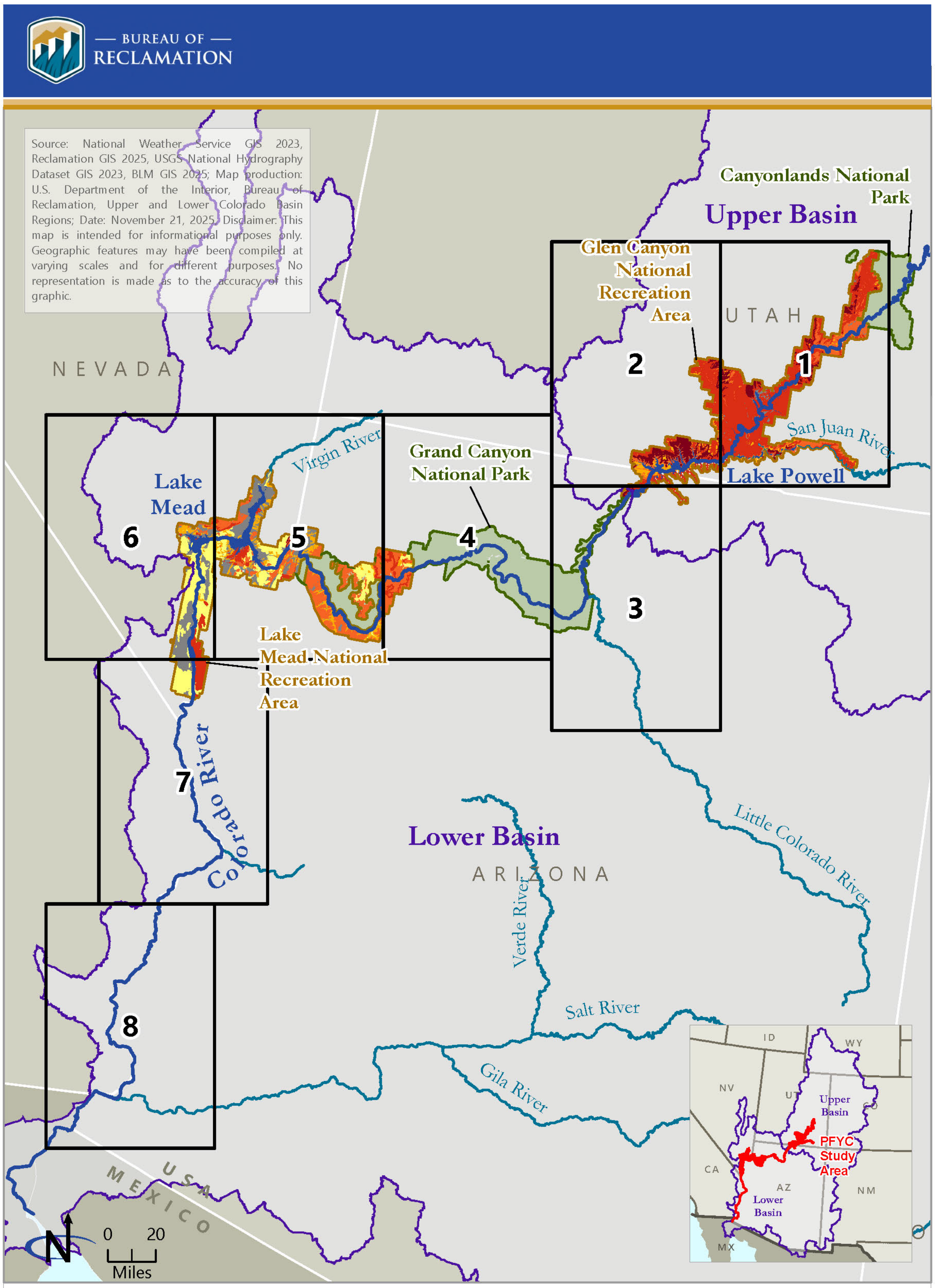
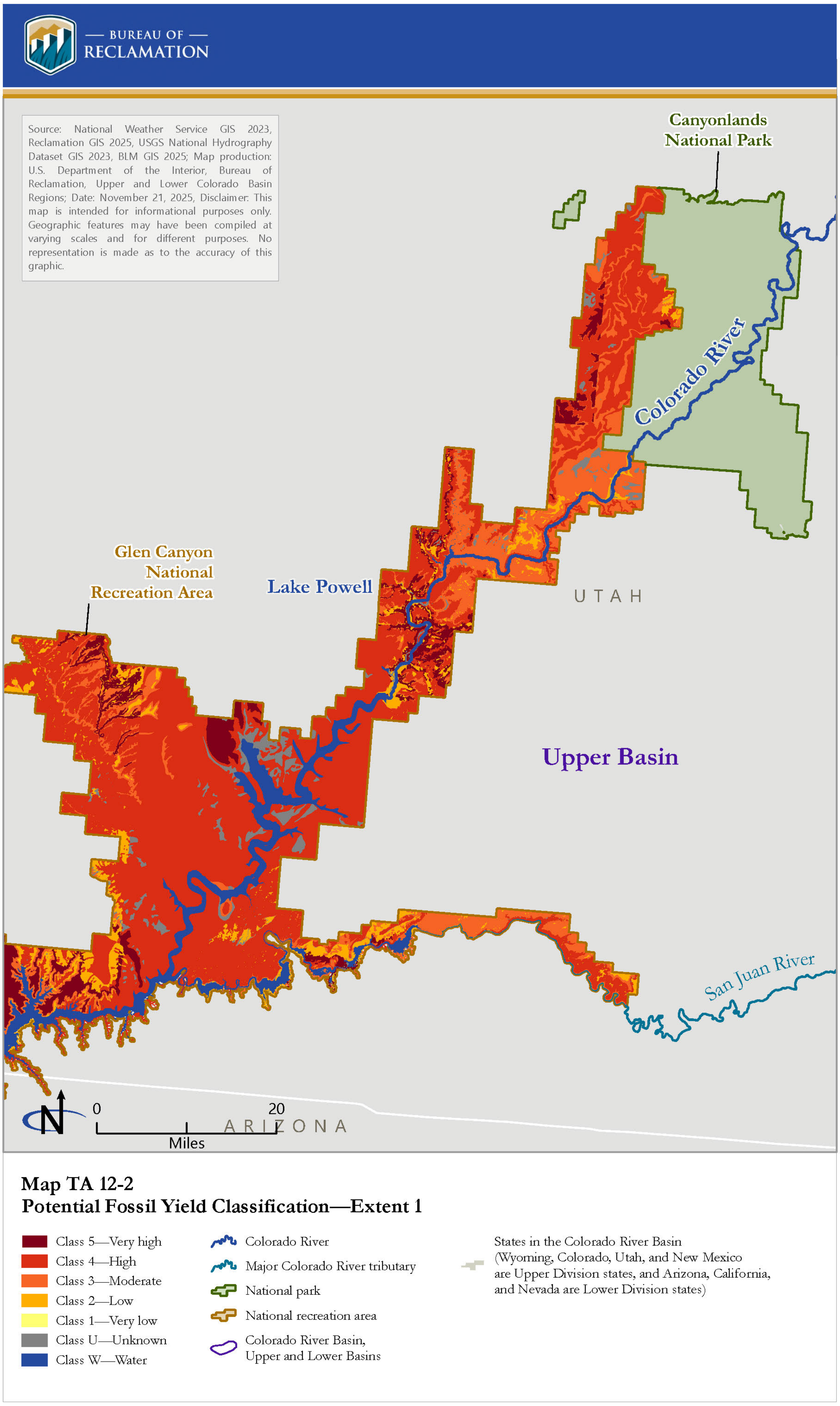
Map TA 12-1
Potential Fossil Yield Classification—Overview



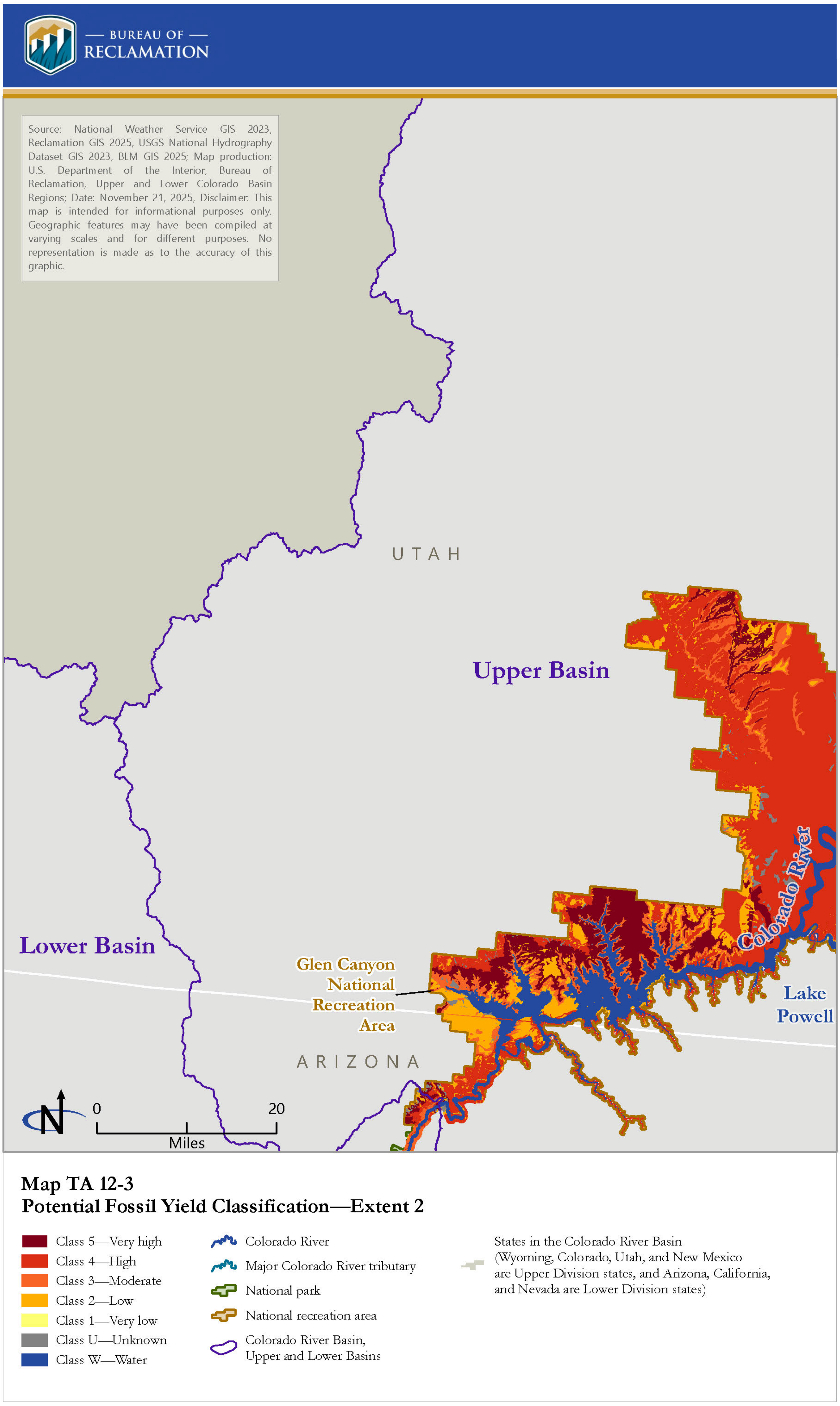
Map TA 12-1
Potential Fossil Yield Classification—Overview

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

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

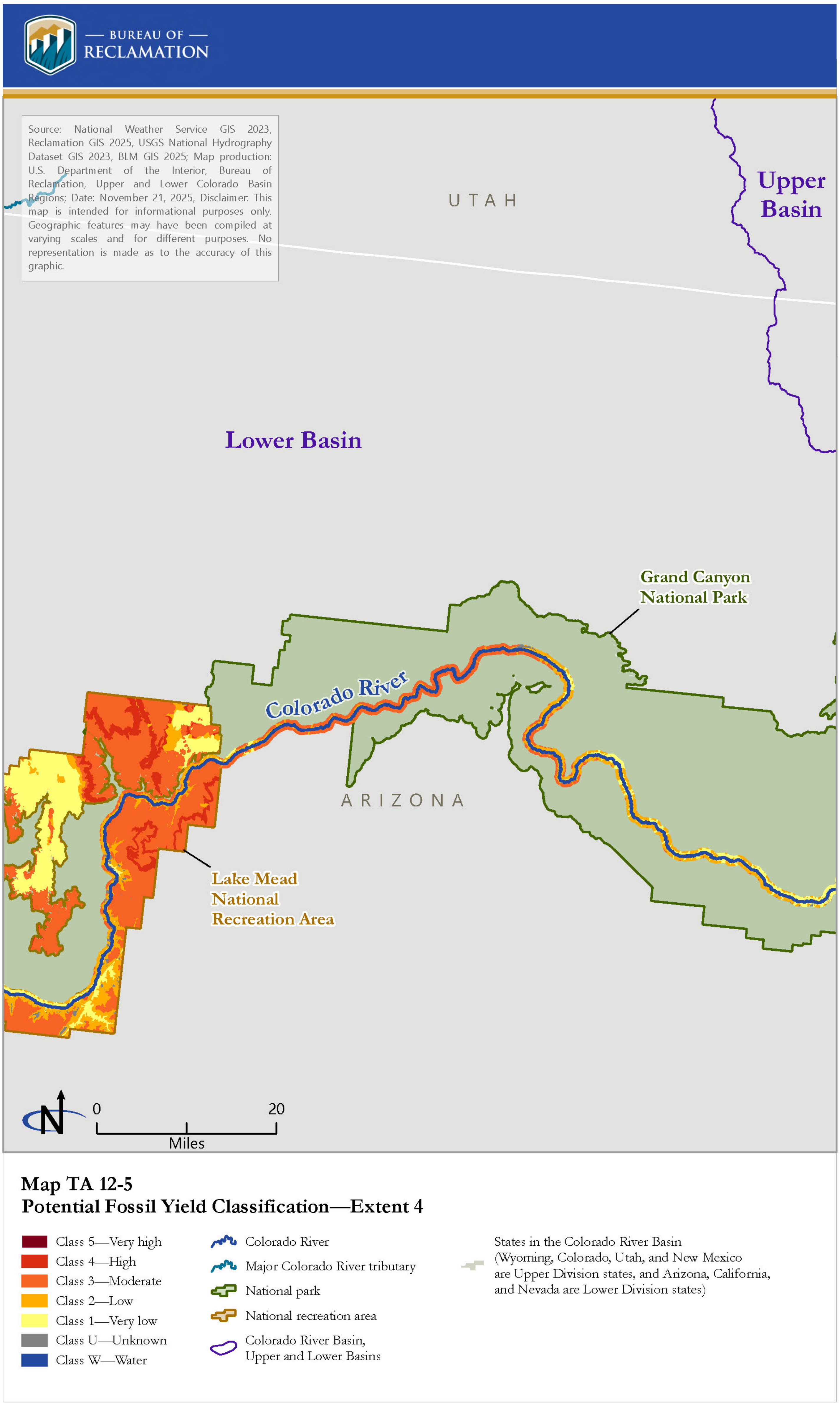


Map TA 12-3
Potential Fossil Yield Classification—Extent 2

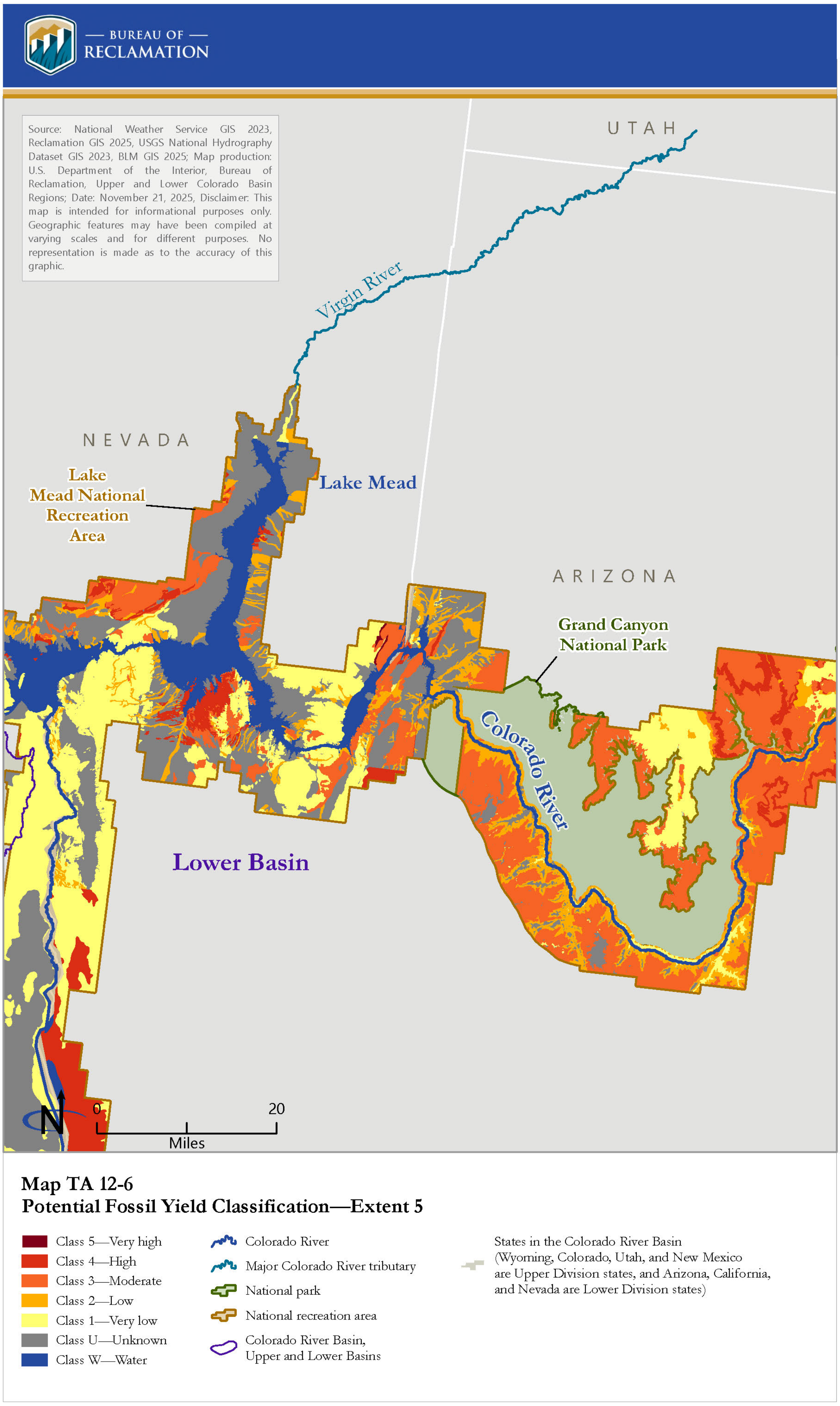


Map TA 12-4
Potential Fossil Yield Classification—Extent 3

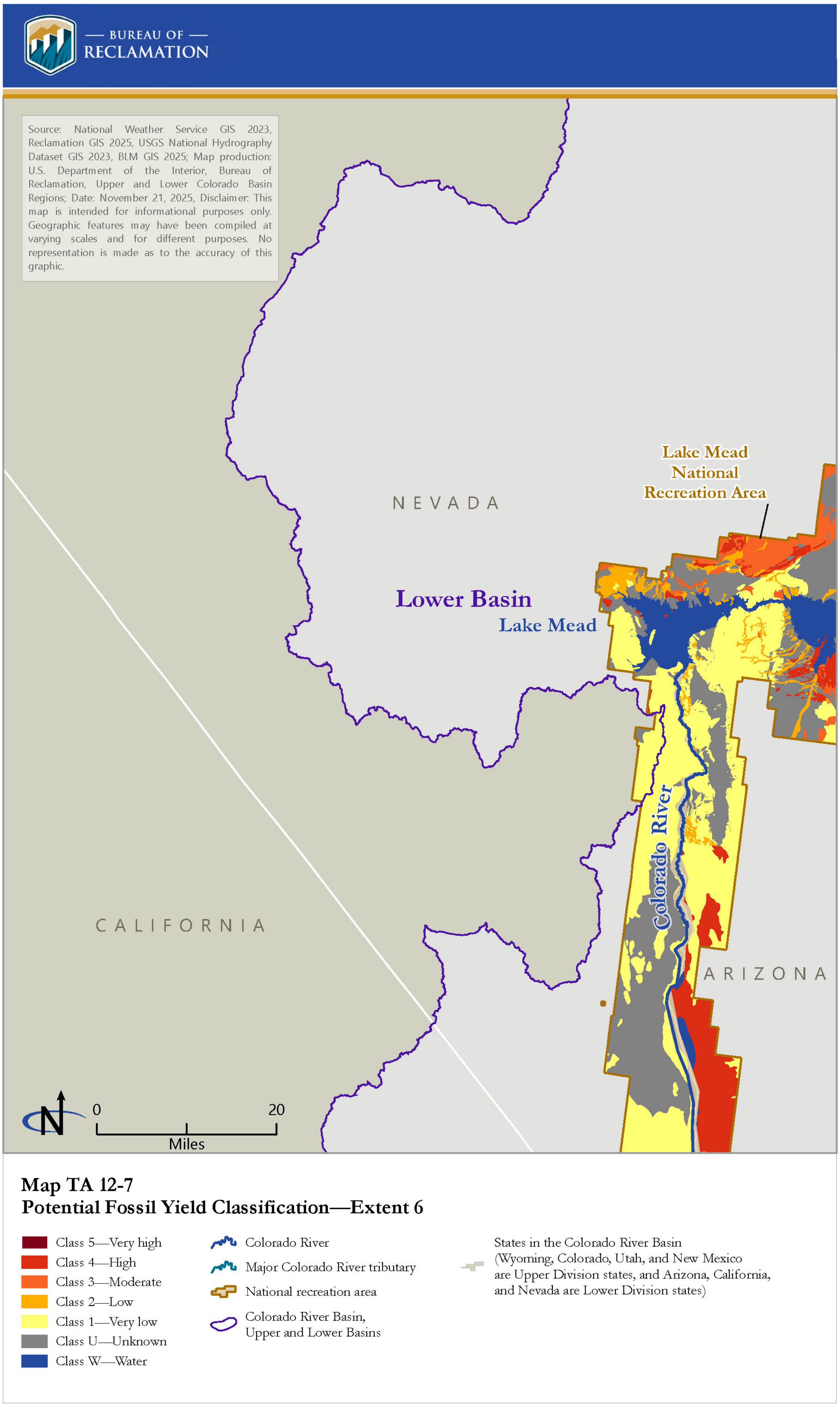
Map TA 12-5
Potential Fossil Yield Classification—Extent 4



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



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



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

Map TA 12-9
Potential Fossil Yield Classification—Extent 8

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Table TA 12-2
Geologic Units and their PFYC Value within the Study Area

PFYC Value	Geologic Unit	Geologic Age
U	Alluvial and eolian deposits Alluvial deposits Alluvial fan and eolian deposits Alluvial fan deposits with eolian mantle Alluvial fan, stream, eolian, and colluvial deposits Alluvial gravel (local sources) Alluvial gravel deposits of the Colorado River Alluvial gravels, undifferentiated Alluvial river or stream deposits Alluvial river or stream terrace gravel deposits Alluvial terrace gravel deposits Alluvium Calcrete Colluvium Colluvium and talus Colorado River gravel and silt deposits Deposits of Jumbo Pass Fanglomerate Gravel deposits Gypsum and gypsiferous siltstone facies of the Rocks of the Grand Wash Trough Interbedded mainstream gravels of Grand Wash Intermediate-age piedmont alluvium Intermediate-age sedimentary rocks, younger Intermediate-age sidestream alluvium Lacustrine deposits Landslide deposits Level 1 alluvial terrace deposits Level 2 alluvial terrace deposits Level 3 alluvial and eolian deposits Level 3 alluvial river terrace deposits	Cenozoic

PFYC Value	Geologic Unit	Geologic Age
	Level 3 Alluvial river terrace deposits with eolian mantle Level 3 alluvial terrace deposits Level 4 alluvial river terrace deposits Level 4 alluvial river terrace deposits with eolian mantle Level 4alluvial river terrace deposits Level 5 alluvial river terrace deposits Level 5 alluvial river terrace deposits with eolian mantle Level 6 alluvial river terrace deposits Level 8 Alluvial river terrace deposits Limestone and siltstone facies of the Rocks of the Grand Wash Trough Lovell Wash Member, limestone and sandstone facies Mainstream alluvium Metasedimentary rocks, undivided Old alluvial deposits, undivided Old alluvial fan deposits Old alluvial fan deposits, undivided Old alluvial terrace deposits, undivided Old alluvium Old gravel deposits Old terrace-gravel deposits Older alluvial and eolian deposits Older alluvial deposits Older alluvial fan, alluvial plain, and pediment deposits Older alluvial terrace deposits Older eolian sand, silt, and carbonate deposits Older eolian sand, silt, and carbonate deposits Older gravels Older intermediate-age sedimentary rocks Older lake beds Older piedmont alluvium Older piedmont alluvium, deposits of ancestral Sacramento Wash Older sidestream alluvium Older terrace-gravel deposits	

PFYC Value	Geologic Unit	Geologic Age
	Oldest terrace-gravel deposits Overton Arm, Conglomerate facies Overton Arm, Gypsiferous facies Overton Arm, Sandstone, siltstone and mudstone facies Paleozoic-clast conglomerate Proterozoic-clast conglomerate facies of the Rocks of the Grand Wash Trough Pyroclastic deposits Red siltstone, sandstone, and conglomerate facies of the Rocks of the Grand Wash Trough Rocks of Overton Arm Rocks of the Grand Wash Trough Rocks of the Grand Wash Trough, Conglomerate facies Rocks of the Grand Wash Trough, Conglomerate facies, bearing granitic and metamorphic clasts Rocks of the Grand Wash Trough, Conglomerate facies, bearing limestone clasts Rocks of the Grand Wash Trough, Limestone-clast breccia facies Rocks of the Grand Wash Trough, Proterozoic-clast breccia facies Rocks of the Grand Wash Trough, Sandstone and siltstone facies Sandstone and conglomerate Sedimentary deposits Sedimentary rocks Sidestream alluvium Stream alluvium Surficial alluvium and colluvium Surficial deposits surficial eolian deposits surficial older alluvium and colluvium Talus and rockfall deposits Talus and rock-fall deposits Talus deposits Talus deposits with eolian sand Terrace gravel and sand Terrace gravel deposits Travertine deposits Tuff of Hoover Dam	

PFYC Value	Geologic Unit	Geologic Age
	Undifferentiated gravel deposits of the Hualapai Plateau Undivided inactive alluvium Unnamed deposits Unnamed nonmarine deposits Upper sedimentary and volcanic sequence, Gneiss-clast conglomerate Upper sedimentary and volcanic sequence, Volcanic-clast conglomerate Valley-fill deposits very old alluvial deposits, undivided Volcanic and sedimentary rocks of Callville Mesa Volcanic and Sedimentary rocks of Hamblin Mountain, Lower Unit Volcanic and sedimentary rocks of Hamblin Mountain, undivided Volcanic sedimentary rocks of Hamblin Mountain Young alluvial fan deposits Young gravel and sedimentary deposits Younger alluvial deposits Younger alluvial fan, alluvial plain and pediment deposits Younger alluvium Younger intermediate-age sedimentary rocks Younger sedimentary rocks Youngest old terrace-gavel deposits Young-intermediate alluvial fan deposits	
	Old gravel and sedimentary deposits	Mesozoic
	Dolomite and limestone Mesozoic and Paleozoic Sedimentary rocks Metasedimentary rocks, undivided Sedimentary rocks	Paleozoic
1	Andesite breccia of Wilson Ridge Basalt Basalt and andesite dikes, plugs, and necks of the volcanic rocks of the Mount Floyd Volcanic Field Basalt flow of the Whitmore dike swarm Basalt flows Basalt flows along the Colorado River	Cenozoic

PFYC Value	Geologic Unit	Geologic Age
	Basalt flows and minor gravels of Grand Wash Basalt flows of Older basalts Basalt flows of the Basalt of the Shivwits Plateau Basalt flows of the Basalt of the Uinkaret Plateau Dikes and plugs Dikes of Colorado River Mile 202 Dikes of Parashant Canyon and Hundred and Ninetysix Mile Creek Fortification Hill basalt Gneiss-clast megabreccia Granite-clast megabreccia Higher basalt flows Intermediate age basalts Intermediate-age megabreccia deposits Intermediate-age rhyolitic to andesitic volcanic rocks Intrusive dikes of the Snap Point Basalt and Garrett dikes Intrusive dikes of the Whitmore dike swarm Intrusive dikes of Young Basalts Intrusive rocks Intrusive rocks of the Basalt of the Shivwits Plateau Lovell Wash Member, interbedded basalt flows and vents Lower volcanic sequence Mafic dikes Middle Mount Davis Volcanics, Mafic lavas Older basalts Overton Arm, Breccia facies Paint Pots pluton of Mills Pasty Mine Volcanics, Lower part Pasty Mine Volcanics, Rhyolite lava Pasty Mine Volcanics, Upper part Pasty Mine Volcanics, Volcanic rocks, undivided Patsy Mine Volcanics Pliocene and Miocene volcanic and plutonic rocks Pyroclastic deposits of the Basalt of the Shivwits Plateau	

PFYC Value	Geologic Unit	Geologic Age
	Pyroclastic deposits of the Basalt of the Uinkaret Plateau Shivwits basalt; Basalt flows Shivwits basalt; Intrusive rocks Tertiary intrusion Upper Mount Davis Volcanics, Dacite intrusions Upper Mount Davis Volcanics, Mafic lavas Upper Mount Davis Volcanics, Rhyodacite and dacite Volcanic deposits, undivided Volcanic rocks Volcanic rocks near Temple Bar, Andesite breccias and lahars Volcanic rocks near Temple Bar, Andesite flows Volcanic rocks near Temple Bar, Olivine basalt and basaltic andesite flows, breccias and mudflows Volcanic rocks near Temple Bar, Pyroxene andesite flows and breccias Volcanic rocks near Temple Bar, Rhyolite breccia Volcanic rocks near Temple Bar, Rhyolite breccia and ignimbrite Volcanic rocks near Temple Bar, Rhyolite ignimbrite Volcanic rocks near Temple Bar, Volcanic sediments, breccias, mudflows and minor, thin ignimbrites Volcanic rocks of Boulder Wash Volcanic rocks of the Hualapai Plateau; Andesite flows and basalt flows Volcanic rocks of the River Mountains Wilson Ridge pluton Wilson Ridge pluton, Horsethief Canyon diorite Wilson Ridge pluton, Teakettle Pass suite Younger basalts Younger rhyolitic to andesitic volcanic rocks	
	Chemehuevi Mountains Plutonic Suite, Biotite granodiorite Chemehuevi Mountains Plutonic Suite, Porphyritic hornblende-biotite granodiorite Holocrystalline rock Intrusive igneous rocks of all ages, undivided Intrusive rocks Mesozoic Metamorphic rocks Metamorphic rocks, medium- to high-grade, undivided Undifferentiated intrusive rocks	Mesozoic

PFYC Value	Geologic Unit	Geologic Age
	Bass Formation Brahma Schist Brahma Schist of Granite Gorge Metamorphic Suite Carbonate and chert Cardenas Basalt Cloritic brecciated gneiss Completely retrograded garnet gneiss Diorite and gabbro Diorite, gabbro, and anorthosite Dox Formation; Comanche Point Member Dox Formation; Ochoa Point Member Dox Formation; Solomon Temple Member Elves Chasm pluton Escalante Creek Member of the Dox Formation within the Unkar Group Galeros Formation; Tanner Member Garnet Gneiss Gneiss Gold Butte Granite Granite Granite of Burro Spring Granite, granitic pegmatite and aplite Granite, granitic pegmatite, and aplites Granitic gneiss Granitiic gneiss Granodiorite complexes Granodiorite-gabbro-diorite and granodiorite complexes Hakatai Shalenite, granitic pegmatite and aplite Intermediate metavolcanic rocks Intrusive igneous rocks of all ages, undivided Intrusive rocks Leucogranite and pegmatite gneiss Mafic metavolcanic rocks Megacrystic granite	Precambrian

PFYC Value	Geologic Unit	Geologic Age
	Mesozoic intrusive rocks Metamorphic and plutonic rocks, undifferentiated Metamorphic and plutonic rocks, undivided Metamorphic rocks, medium- to high-grade, undivided Metamorphosed Sedimentary and Volcanic rocks Metasedimentary and metavolcanic rocks, undivided Mylonitic gneiss and migmatite Nankoweap Formation Orthoamphibole schist Orthoamphibole-bearing gneiss Partly retrograded garnet gneiss Precambrian rocks Proterozoic rocks Quartz diortie gneiss Quartz syenite gneiss Rama Schist Rama Schist and Gneiss of Granite Gorge Metamorphic Suite Schist Shinumo Quartzite Shinumo Sandstone, undivided Ultramafic rocks Undivided igneous and metamorphic rocks; basement complex Unnamed diabase sills and dikes Vishnu Schist Vishnu Schist of Granite Gorge Metamorphic Suite Young granite and pegmatite	

PFYC Value	Geologic Unit	Geologic Age
2	Alluvial and colluvial deposits Alluvial and eolian deposits Alluvial deposits, undivided Alluvial fan deposits Alluvial fan deposits, undivided Alluvial terrace deposits, undivided Alluvial wash deposits, undivided Alluvium of the modern Colorado River flood plain Artificial fill Artificial fill and other land disturbances Artificial fill and quarries Axial alluvial wash deposits Boulder conglomerate of Bat Cave Wash Colorado River gravel deposits Disturbed ground Dredged sand Dune sand and sand sheet deposits Eolian and alluvial deposits Eolian and alluvial sand and silt Eolian sand Eolian sand dune deposits Eolian, alluvial stream, and alluvial fan deposits Flood-plain deposits Historic landslides and slumps Horse Spring Formation, Bitter Ridge Limestone Mem, breccia facies: Thumb Mem, fine-grained facies Horse Spring Formation, undivided Intermediate alluvial fan deposits Intermediate alluvial gravel deposits Intermediate terrace-gravel deposits Intermediate-age sedimentary rocks, older Lacustrine and playa deposits, undivided Landslide deposits Landslide masses	Cenozoic

PFYC Value	Geologic Unit	Geologic Age
	Landslides and slumps Level 2 alluvial and eolian deposits Level 6 alluvial gravel deposits Linear dune deposits Marsh deposits Mass movement landslide and slump deposits Mass-movement landslide and talus deposits Mass-movement landslides, slumps, and talus, undifferentiated Mass-movement slump blocks Mass-movement talus deposits Middle Mount Davis Volcanics, Tuff of Hoover Dam Mixed alluvial fan, colluvial, and eolian deposits Mixed eolian and alluvial deposits Mixed eolian and alluvial sand deposits Mount Davis Volcanics, Sedimentary rocks Old alluvial fan deposits Old terrace-gravel deposits Parabolic dune deposits Pasty Mine Volcanics, Middle part, undivided Pasty Mine Volcanics, Sedimentary rocks Peach Spring Tuff Ponded sediments Post–Hoover Dam channel deposits Pre–Hoover Dam channel deposits Pre–Hoover Dam floodplain deposits Proximal-floodplain deposits Rainbow Gardens Member of the Horse Spring Formation Sand sheet deposits Sedimentary breccia Sedimentary rocks Slumps and landslides Stream-channel alluvium Stream-channel deposits	

PFYC Value	Geologic Unit	Geologic Age
	Surficial landslide deposits Travertine deposits Tufa Tuff of Bridge Spring Upper sedimentary and volcanic sequence, Conglomerate Valley-fill deposits Volcanic rocks Volcanic rocks of Boulder Wash, gypsiferous facies Young alluval stream deposits with eolian sand Young alluvial deposits, undivided Young alluvial fan deposits Young alluvial fan deposits, undivided Young alluvium Young mixed alluvium and eolian deposits Young terrace-gravel deposits Younger alluvial deposits Younger alluvial river deposits Younger piedmont alluvium Younger rhyolitic ash-flow tuffs Youngest piedmont alluvium	
	Carmel Formation, Paria River Member Carmel Formation, Upper Members Carmel Formation, upper members (Paria River and Winsor Mbrs) Carmel Formation, Winsor Member Chinle Formation, Shinarump Member Entrada Sandstone Romana Sandstone	Mesozoic
	Arkosic facies of Cutler Formation Bright Angel Shale Bright Angel Shale of the Tonto Group Cambrian rocks, undifferentiated Morgan, Round Valley, Honaker Trail, Paradox, Ely and other Fms	Paleozoic

PFYC Value	Geologic Unit	Geologic Age
	Muav Formation Muav Limestone Muav Limestone of the Tonto Group Tapeats Sandstone Tapeats Sandstone and Bright Angel Shale, undivided Tapeats Sandstone of the Tonto Group White Rim Sandstone White Rim Sandstone (part of Cutler Group)	
3	Alluvial deposits Alluvial-fan deposits Alluvium Bitter Ridge Limestone Horse Spring Formation Hualapai Limestone Thumb Member, breccia and landslide matches Thumb Member, conglomeratic rock Thumb Member, fine-grained facies Thumb Member, gypsum facies Undifferentiated alluvial deposits Upper member (Monitor Butte, Mossback, Petrified Forest, Owl Rock, and Church Roc Upper members (Monitor Butte, Mossback, Petrified Forest, Owl Rock, and Church R Upper members of Chinle Formation Wescogame Formation, Manakacha Formation, and Watahomigi Formation, undivided of the Supai Group Wescogame, Manakacha, and Watahomigi Formations Wescogame, Manakacha, and Watahomigi Formations, undivided of the Supai Group Wingate Formation Wingate sandstone Woods Ranch, Brady Canyon, and Seligman Members, undivided of the Toroweap Formation	Cenozoic
	Carmel Formation Carmel Formation, undivided Carmel Formation, undivided (mostly Paria River and Winsor Mbrs) Chinle Fm,upper unit (Church Rock[Rock Point],Owl Rock,and Petrified Forest Mbrs)	Mesozoic

PFYC Value	Geologic Unit	Geologic Age
	Chinle, Ankareh Fms Dakota Sandstone Entrada Sandstone Limestone and dolominte beds in Navajo Sandstone Moenave and Kayenta Formations, undivided Moenkopi Formation San Rafael Group Sedimentary rocks Shinarump Conglomerate Member of Chinle Formation Straight Cliffs Formation, lower unit (Smoky Hollow and Tibbet Canyon Mbrs) Upper member (Monitor Butte, Mossback, Petrified Forest, Owl Rock, and Church Roc Upper members (Monitor Butte, Mossback, Petrified Forest, Owl Rock, and Church R Upper members of Chinle Formation Wingate Formation Wingate sandstone	
	Cedar Mesa Sandstone Cedar Mesa Sandstone (part of Cutler Group) Cedar Mesa, Diamond Creek, Arcturus and other Fms Coconino Sandstone Esplanade Sandstone Esplanade Sandstone and Pakoon Limestone Esplanade Sandstone and Pakoon Limestone, undivided Esplanade Sandstone of the Supai Group Fossil Mountain Member of the Kaibab Formation Harrisburg and Fossil Mountain Members, undivided of the Kaibab Formation Harrisburg Member of the Kaibab Formation Hermit Formation and Esplanade Sandstone, undivided Honaker Trail Formation Honaker Trail Formation (part of Hermosa Group) Kaibab and Toroweap Formations, undivided Kaibab Formation Kaibab Formation; Fossil Mountain Member Kaibab Formation; Harrisburg Member	Paleozoic

PFYC Value	Geologic Unit	Geologic Age
	Monte Cristo Group Muav Formation Oquirrh Group, Wells, Weber, Ely, Callville and other Fms Organ Rock Formation Organ Rock Shale Organ Rock Shale (part of Cutler Group) Pakoon and Callville Limestones Pakoon Limestone and Callville Formation, undivided Paradox Formation Pogonip Group Redwall Limestone Sultan Limestone Supai Formation Supai Group, undivided Surprise Canyon Formation Temple Butte Formation Toroweap Formation Toroweap Formation, Brady Canyon and Seligman Members Toroweap Formation; Brady Canyon Member Toroweap Formation; Seligman Member Toroweap Formation; Woods Ranch Member Wescogame Formation, Manakacha Formation, and Watahomigi Formation, undivided of the Supai Group Wescogame, Manakacha, and Watahomigi Formations Wescogame, Manakacha, and Watahomigi Formations, undivided of the Supai Group Woods Ranch, Brady Canyon, and Seligman Members, undivided of the Toroweap Formation	
4	Chemehuevi Formation Chemehuevi Formation, gypsiferous mud Chemehuevi Formation, sand Muddy Creek Formation Muddy Creek Formation, Fine-grained facies Muddy Creek Formation, Gypsum facies Muddy Creek Formation, Limestone facie Muddy Creek Formation, Tuff bed	Cenozoic

PFYC Value	Geologic Unit	Geologic Age
	Sedimentary deposits	
	Aztec Sandstone Chinle Formation Dakota Formation Glen Canyon Group Glen Canyon Group (Navajo, Kayenta, Wingate, Moenave Fms) and Nugget Ss Hoskinnini Sandstone Member Hoskinnini Sandstone Member of Moenkopi Formation Judd Hollow Tongue and Page Sandstone Tongues Kayenta Formation Kayenta Formation, undivided Lower red member, Virgin Limestone Member, & middle red member, undivided of the Moenkopi Formation Moenave Formation and Wingate Sandstone, undivided Moenkopi Formation Moenkopi Formation, undivided Moenkopi Formation; Timpoweap Member Moenkopi Formation; Upper red member Moenkopi, Dinwoody, Woodside, Thaynes and other Fms Moss Back Member of Chinle Formation Navajo Sandstone Navajo Sandstone of the Glen Canyon Group Page Sandstone Page Sandstone and Judd Hollow Tongue of Carmel Formation Page Sandstone and Judd Hollow Tongue of Carmel Formation, undivided Shnabkaib Member of the Moenkopi Formation Springdale Sandstone Member Straight Cliffs Formation, John Henry Member Summerville, Entrada, Carmel, Arapien, Twin Creek and other Fms Temple Cap Formation Tropic Shale Upper member of Moenkopi Formation	Mesozoic

PFYC Value	Geologic Unit	Geologic Age
	Hermit Formation Hermit Formation and Esplanade Sandstone, undivided Lower Cutler beds Lower Cutler beds (part of Cutler Group) Lower member of Halgaito Formation Lower member of Honaker Trail Formation Upper member of Halgaito Formation Upper member of Honaker Trail Formation	Paleozoic
5	Chinle Formation Chinle Formation, lower part, undivided Chinle Formation, undivided Chinle Formation, upper part (Church Rock, Owl Rock, Petrified Forest, and Monit) Chinle Formation, upper part, undivided Church Rock Member of Chinle Formation Dakota Formation Dakota, Cedar Mountain, Kelvin and other Fms Monitor Butte Member of Chinle Formation Morrison Fm 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 Upper members of Chinle Formation	Mesozoic
	Tapeats Sandstone and Bright Angle Shale	Paleozoic

Source: BLM GIS 2025

Lake Powell and Glen Canyon Dam

The Glen Canyon National Recreation Area (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 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 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 the Dinosaur Canyon Member of the Moenave Formation in the southern areas of Glen Canyon NRA—all known to be fossiliferous at localities outside of 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 has completed 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.

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 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, the present-day Lake Mead underwent a period of extensive erosion which resulted in a geological gap between the rock record of fossils until the later portion of the Cenozoic era. Lake Mead has documented an impressive list of fossils from the Oligocene Epoch of the Cenozoic era, particularly in the forms of mammals, amphibians, birds, and reptiles (NPS 2022).

A comprehensive paleontological resource inventory was completed for Lake Mead NRA in 2018 by NPS. 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.

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 geological 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 survey 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—spanning 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. A paleontological resources inventory of the entire corridor was completed in 2020 by Reclamation (Bonde and Slaughter 2020). This report is confidential to Reclamation as 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, accelerating their 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 as well as a popular outlet for recreation. Possible water-related impacts that result in the threat or loss of paleontological resources in the study area include:

- Flooding events or controlled capture of reservoir levels leading to the elevation of water levels and consequent submersion of fossiliferous Phanerozoic geological exposures.
- Controlled release of reservoir waters resulting 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 (i.e., the steep canyon walls of the Grand Canyon carved by the Colorado River) which 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 is variable. 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**). Therefore, the erosion concerns at Lake Powell are extremely high, as these conditions are impacting geologic units with high and very high paleontological value.

TA 12.2 Environmental Consequences

TA 12.2.1 Methodology

Direct and indirect impacts on paleontological resources could result from changes in lake levels or river flows from the annual releases. Of greatest concern are effects on paleontological resources that degrade or damage those resources before they can be preserved. Direct impacts may occur from processes such as wave action and wet-dry cycling and 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 modelling developed by the U.S. Geological Survey (USGS) and NPS and aeolian transport-vegetation cover-High-Flow Experiment (HFE) joint modeling also developed by USGS. Additionally, PFYC data were used to analyze areas of high fossiliferous potential within the impact analysis area.

Potential Fossil Yield Classification 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, PFYC 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) scale, with a "U" category for unknown or understudied areas. PFYC is continuously updated by BLM and other agencies and was used to map the entire study area.

Preservation Risk Modeling

USGS, in cooperation with 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 which considers several landscape characteristics, locations of previously recorded paleontological resources, and potential for water-related impacts such as wave action and erosion. The lake landscape was gridded into 10 meter-resolution cells, and each cell was ranked 1 to 5 based on low (1) to high (5) potential for resource preservation to be impacted by water at a given reservoir elevation. The ranking incorporates two other models: 1) the PFYC model, 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.

For paleontological resources, the Resource Distribution Model is based on geologic landscape divisions and PFYC-informed resource locations. The PFYC by landscape division metric is used to produce the resource distribution model rank, ranging from 1 (very low potential) to 5 (very high potential).

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 (the distance wind travels over water surfaces to generate waves), 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 (USGS 2025). Human impacts, such as vandalism or unauthorized collection, are not included in this model.

When combining the Resource Distribution 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 impacted by lake management actions; 2) even where resource likelihood is low, hazards from water levels can impact a potentially significant resource; 3) areas with 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 very low likelihood of containing resources and very low potential for impacts are at the lowest risk of resource condition changes.

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," Kasprak et al. 2004), 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 (Sankey et al. 2018). 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 for 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, 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 broad-scale 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 is limited.
- Landforms with steeper slopes are more susceptible to wave action erosion compared with low-slope areas.

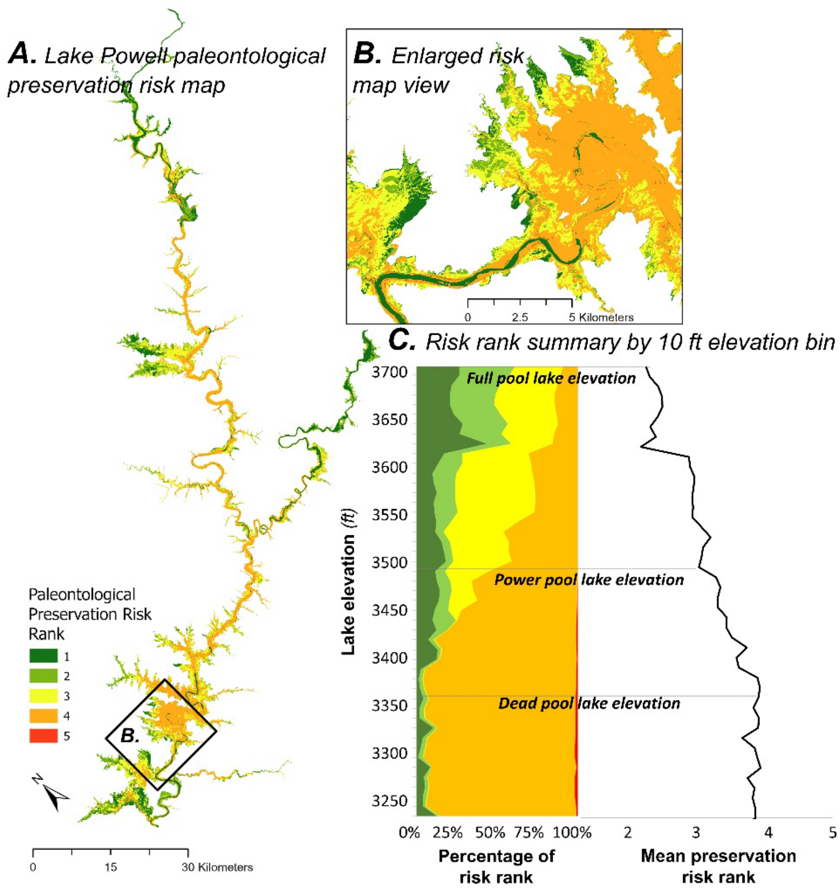
Impact Indicators

- 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 sand bar building and availability of windblown sediments to protect paleontological localities or exposed fossils.

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?

USGS, in cooperation with NPS, created the Paleontological Preservation Risk Model, which was utilized in the decision making under deep uncertainty (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 depicts the relationship between lake elevation and preservation risk rank at Lake Powell (Caster et al. 2026). This relationship can be extrapolated to general reservoir conditions; the same trend is true for Lake Mead.

Figure TA 12-3
C. Risk Rank Summary at Lake Powell



Source: USGS Modeling Report 2025

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), more paleontological resources that have likely never been exposed 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 paleontology 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 impacted 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 in paleontological resources subjected to similar processes.

Lake Powell

This section presents a comparison of the No Action Alternative, Continued Current Strategies (CCS) Comparative Baseline, and action alternatives with respect to paleontological preservation risk at Lake Powell. 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 in Lake Powell preservation risk because they use the same operation of Lake Powell. **Table TA 12-3** below shows the statistical breakdown of preservation risk rank at Lake Powell for each of the different hydrologic conditions under different alternatives. These values include the maximum, 90th percentile, 75th percentile, median, 25th percentile, 10th percentile, and minimum preservation risk rank.

Table TA 12-3
Water Year Maximum Paleontological Preservation Risk at Lake Powell

Alternative (including CCS Comparative Baseline)	Flow Category (maf*)	Max	90th percentile	75th percentile	Median	25th percentile	10th percentile	Min
CCS Comparative Baseline	> 16	3.17	**2.45**	**2.45**	**2.44**	**2.39**	**2.39**	**2.26**
CCS Comparative Baseline	14-16	3.32	2.93	2.93	**2.45**	**2.44**	**2.39**	**2.26**
CCS Comparative Baseline	12-14	3.71	3.17	3.06	2.93	**2.85**	**2.44**	**2.26**
CCS Comparative Baseline	10-12	3.71	3.32	3.32	3.17	2.93	**2.91**	**2.35**
CCS Comparative Baseline	< 10	3.71	3.71	3.49	3.32	3.17	3.04	**2.35**

Alternative (including CCS Comparative Baseline)	Flow Category (maf*)	Max	90th percentile	75th percentile	Median	25th percentile	10th percentile	Min
No Action	> 16	3.17	**2.45**	**2.44**	**2.39**	**2.39**	**2.39**	**2.26**
No Action	14-16	3.41	2.93	**2.87**	**2.45**	**2.39**	**2.39**	**2.26**
No Action	12-14	3.71	3.32	3.17	2.93	**2.45**	**2.44**	**2.26**
No Action	10-12	3.71	3.41	3.41	3.32	2.93	**2.45**	**2.35**
No Action	< 10	3.71	3.71	3.71	3.41	3.32	2.93	**2.35**
Basic Coord.	> 16	3.04	**2.45**	**2.45**	**2.44**	**2.39**	**2.39**	**2.26**
Basic Coord.	14-16	3.32	2.93	**2.87**	**2.45**	**2.44**	**2.38**	**2.26**
Basic Coord.	12-14	3.71	3.17	3.04	2.93	**2.85**	**2.45**	**2.35**
Basic Coord.	10-12	3.71	3.41	3.32	3.17	2.93	**2.92**	**2.35**
Basic Coord.	< 10	3.71	3.71	3.71	3.41	3.17	3.06	**2.87**
Enhanced Coord.	> 16	2.93	**2.45**	**2.45**	**2.44**	**2.39**	**2.39**	**2.26**
Enhanced Coord.	14-16	3.17	**2.85**	**2.45**	**2.45**	**2.44**	**2.38**	**2.13**
Enhanced Coord.	12-14	3.25	2.93	**2.87**	**2.45**	**2.44**	**2.35**	**2.13**
Enhanced Coord.	10-12	3.32	3.06	2.93	**2.92**	**2.85**	**2.38**	**2.13**
Enhanced Coord.	< 10	3.71	3.28	3.17	3.04	**2.92**	**2.87**	**2.13**
Max. Op. Flexibility	> 16	2.93	**2.45**	**2.45**	**2.44**	**2.39**	**2.39**	**2.26**
Max. Op. Flexibility	14-16	3.17	**2.85**	**2.45**	**2.45**	**2.44**	**2.38**	**2.26**
Max. Op. Flexibility	12-14	3.17	2.93	2.93	**2.85**	**2.45**	**2.38**	**2.27**
Max. Op. Flexibility	10-12	3.17	3.17	2.93	2.93	**2.91**	**2.85**	**2.35**
Max. Op. Flexibility	< 10	3.71	3.17	3.17	3.06	2.93	**2.92**	**2.35**
Supply Driven (LB Priority)	> 16	3.17	**2.87**	**2.45**	**2.45**	**2.44**	**2.39**	**2.26**
Supply Driven (LB Priority)	14-16	3.32	3.04	2.93	**2.87**	**2.45**	**2.38**	**2.26**
Supply Driven (LB Priority)	12-14	3.41	3.17	3.17	2.93	**2.92**	**2.85**	**2.35**
Supply Driven (LB Priority)	10-12	3.49	3.32	3.25	3.17	3.04	**2.92**	**2.35**
Supply Driven (LB Priority)	< 10	3.71	3.49	3.41	3.32	3.17	3.06	**2.87**

Alternative (including CCS Comparative Baseline)	Flow Category (maf*)	Max	90th percentile	75th percentile	Median	25th percentile	10th percentile	Min
Supply Driven (LB Pro Rata)	> 16	3.17	**2.87**	**2.45**	**2.45**	**2.44**	**2.39**	**2.26**
Supply Driven (LB Pro Rata)	14-16	3.32	3.04	2.93	**2.87**	**2.45**	**2.38**	**2.26**
Supply Driven (LB Pro Rata)	12-14	3.41	3.17	3.17	2.93	**2.92**	**2.85**	**2.35**
Supply Driven (LB Pro Rata)	10-12	3.49	3.32	3.25	3.17	3.04	**2.92**	**2.35**
Supply Driven (LB Pro Rata)	< 10	3.71	3.49	3.41	3.32	3.17	3.06	**2.87**

Note: Ranks in blue are below the historically derived threshold of 2.93. This is the 90th percentile rank from 2008–2024 during the 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.
* maf=million acre-feet.

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 three-year average of Lees Ferry natural flow. The figure visualizes the same data that is included in **Table TA 12-3** 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.

In the Average Flow Category (12–14 maf), 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 (10.0–12.0 maf), 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 (less than 10.0 maf).

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 12-3**).

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 (greater than 16.0 maf), 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.

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

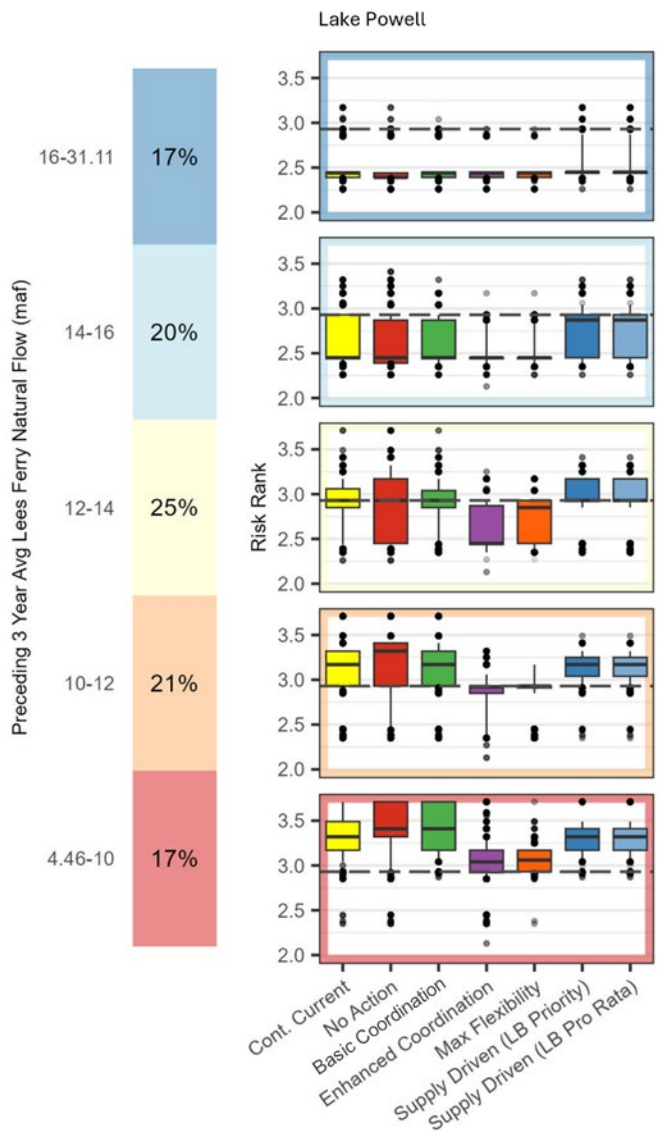
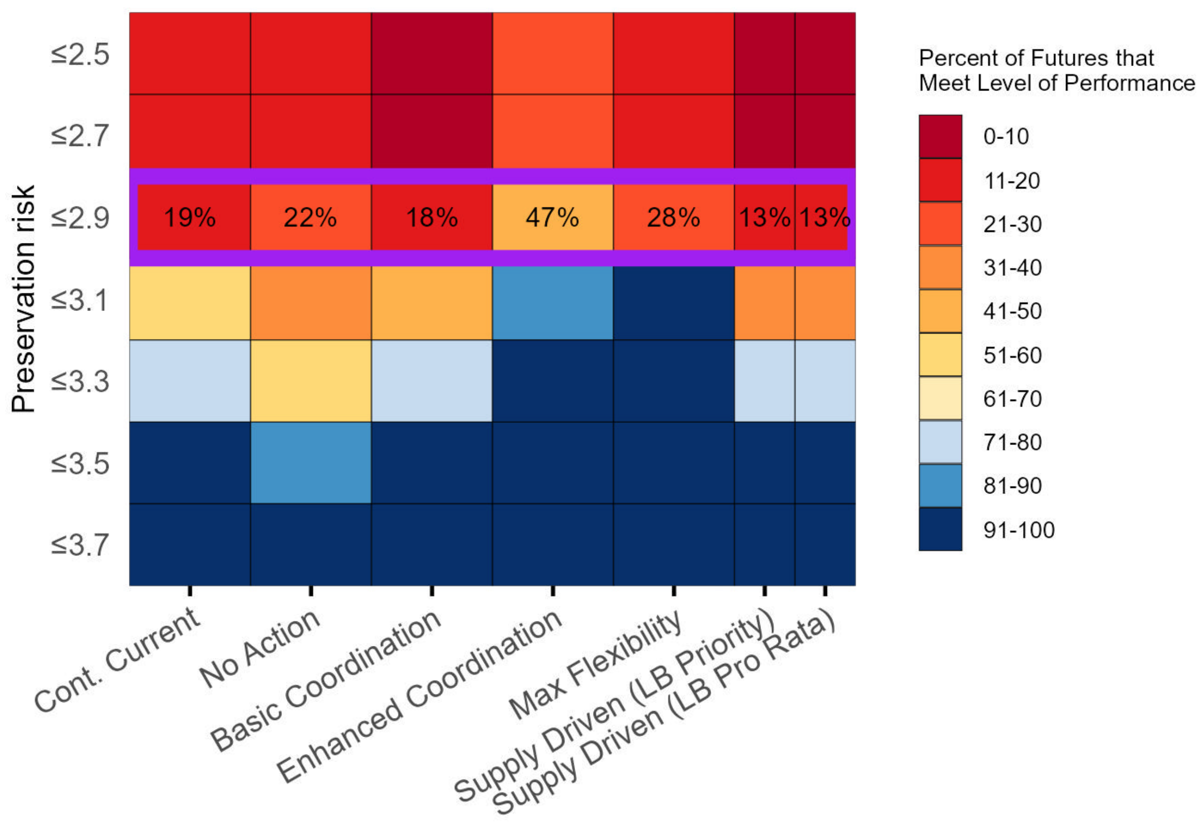


Figure TA 12-5 below depicts the performance of each alternative with respect to keeping paleontological preservation risk ranks at Lake Powell below the historically derived threshold in at least 90 percent of months. This is the same threshold as what was used in **Figure TA 12-4**. The figure is broken 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 sub periods. 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.

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 47 percent of the futures. The Basic Coordination and No Action Alternatives perform similarly to the CCS Baseline, succeeding in 18 percent, 22 percent, and 19 percent of futures, respectively. The Maximum Operational Flexibility Alternative succeeds 28 percent of the time over the full modeling period, which is just similar enough to the CCS 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 13 percent.

Figure TA 12-5
Paleontological Resources in Glen Canyon National Recreation Area: Robustness. Percent of futures in which monthly preservation risk stays below the value specified in each row in at least 90% of months



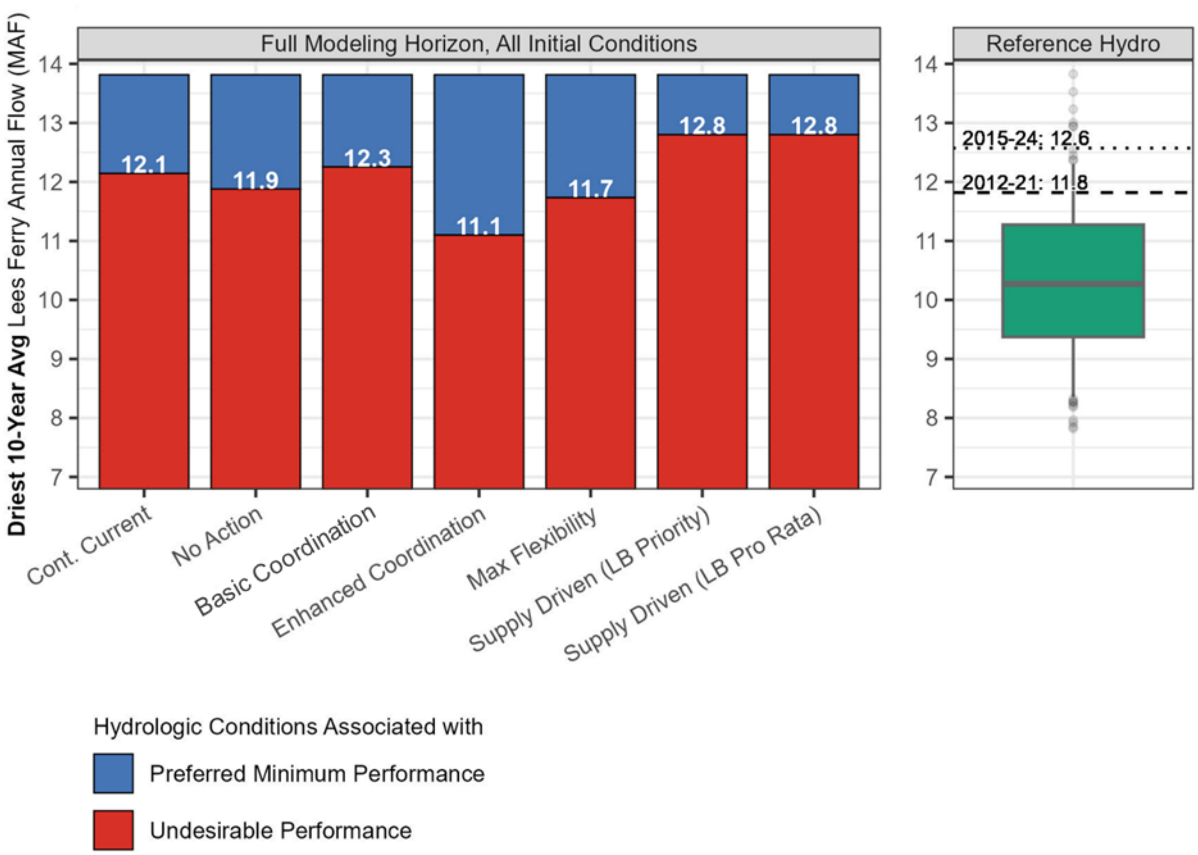
In lower rows of the heat maps, the Maximum Operational Flexibility Alternative begins to perform better more quickly than the Enhanced Coordination Alternative, consistently achieving 91–100 percent robustness by 3.1 and 3.3, respectively, over the full modeling period. The Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) reaches 91–100 percent robustness at

3.5 while the other alternatives and CCS Comparative Baseline reach 91–100 percent robustness at 3.7.

The robustness scores of the alternatives improve when analyzing shorter modeling periods because it is easier to meet the historically derived threshold rank for shorter periods than the full 34-year simulation. The Enhanced Coordination Alternative achieves the highest success of all alternatives in the 2040–2049 period with 65 percent of futures in which monthly preservation risk rank stays below the historically derived threshold.

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. The driest observed 10-year average flow from 2012–2021 (11.8 maf, dashed line) and the average flow from 2015–2024 (12.6 maf, dotted line) are also provided in the reference hydrology for comparison.

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



The Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) results in undesirable performance (i.e., becoming vulnerable to paleontological preservation risk rank exceeding the historically derived threshold), when the future includes a 10-year average flow of 12.8 maf or lower. Nearly all of the reference hydrology traces include average flows of 12.8 or lower; the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) results in futures where paleontological resources are vulnerable to increased risk.

The Enhanced Coordination Alternative results in undesirable performance when the 10-year average flow is below 11.1 maf. Approximately 75 percent of the reference hydrology traces include averages this low or lower. The CCS Comparative Baseline and Basic Coordination Alternative perform similarly, with paleontological resources becoming vulnerable at approximately 12.1 and 12.3 maf, respectively. More than 75 percent of the reference hydrology traces include average flows this low or lower.

The No Action Alternative and Maximum Operational Flexibility Alternative perform similarly to the driest 10-year average flow from 2012–2021 (11.9 maf, 11.7 maf, and 11.8 maf, respectively). Under both alternatives, paleontological resources are vulnerable to conditions that are close to what has already occurred.

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. 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. **Table TA 12-4** below shows the statistical breakdown of preservation risk rank at Lake Mead for each of the different hydrologic conditions under different alternatives. These values include the maximum, 90th percentile, 75th percentile, median, 25th percentile, 10th percentile, and minimum preservation risk rank. The historically derived threshold at Lake Mead is a risk rank of 2.33.

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

Alternative (including CCS Comparative Baseline)	Flow Category (maf)	Max	90th percentile	75th percentile	Median	25th percentile	10th percentile	Min
CCS Comparative Baseline	> 16	2.54	2.35	2.33	**2.21**	**2.2**	**2.18**	**2.08**
CCS Comparative Baseline	14-16	2.75	2.4	2.38	2.33	**2.28**	**2.19**	**2.02**
CCS Comparative Baseline	12-14	2.75	2.54	2.52	2.38	**2.32**	**2.21**	**1.96**
CCS Comparative Baseline	10-12	2.75	2.75	2.54	2.4	2.33	**2.26**	**1.96**
CCS Comparative Baseline	< 10	2.75	2.75	2.54	2.39	**2.25**	**2.22**	**2.05**

Alternative (including CCS Comparative Baseline)	Flow Category (maf)	Max	90th percentile	75th percentile	Median	25th percentile	10th percentile	Min
No Action	> 16	2.59	2.52	2.38	**2.21**	**2.2**	**2.18**	**2.08**
No Action	14-16	2.75	2.59	2.54	2.38	**2.32**	**2.2**	**2.05**
No Action	12-14	2.75	2.59	2.59	2.52	2.36	**2.25**	**2.08**
No Action	10-12	2.75	2.75	2.59	2.52	2.36	**2.25**	**1.96**
No Action	< 10	2.75	2.75	2.59	2.38	**2.22**	**2.14**	**2.08**
Basic Coord.	> 16	2.59	2.35	**2.21**	**2.21**	**2.19**	**2.11**	**2.02**
Basic Coord.	14-16	2.59	2.39	2.35	**2.29**	**2.18**	**2.11**	**1.96**
Basic Coord.	12-14	2.75	2.52	2.38	2.33	**2.21**	**2.16**	**2.02**
Basic Coord.	10-12	2.75	2.59	2.52	2.35	**2.29**	**2.17**	**1.96**
Basic Coord.	< 10	2.75	2.75	2.52	2.35	**2.25**	**2.18**	**2.08**
Enhanced Coord.	> 16	2.54	**2.21**	**2.21**	**2.2**	**2.19**	**2.17**	**2.02**
Enhanced Coord.	14-16	2.59	2.35	2.33	**2.21**	**2.17**	**2.11**	**1.96**
Enhanced Coord.	12-14	2.75	2.38	2.35	2.33	**2.2**	**2.17**	**1.96**
Enhanced Coord.	10-12	2.75	2.52	2.39	2.35	**2.32**	**2.21**	**1.96**
Enhanced Coord.	< 10	2.75	2.59	2.52	2.39	2.33	**2.22**	**2.08**
Max. Op. Flexibility	> 16	2.54	2.32	2.21	**2.2**	**2.2**	**2.18**	**2.08**
Max. Op. Flexibility	14-16	2.59	2.35	2.33	**2.21**	**2.19**	**2.14**	**2.02**
Max. Op. Flexibility	12-14	2.59	2.39	2.33	**2.21**	**2.18**	**2.11**	**2.02**
Max. Op. Flexibility	10-12	2.75	2.52	2.39	2.33	**2.2**	**2.11**	**1.96**
Max. Op. Flexibility	< 10	2.75	2.59	2.52	2.38	**2.26**	**2.17**	**2.02**
Supply Driven (LB Priority)	> 16	2.59	2.21	**2.21**	**2.2**	**2.2**	**2.2**	**2.1**
Supply Driven (LB Priority)	14-16	2.59	2.35	**2.31**	**2.2**	**2.19**	**2.14**	**2.08**
Supply Driven (LB Priority)	12-14	2.75	2.39	2.33	**2.21**	**2.18**	**2.11**	**2.02**
Supply Driven (LB Priority)	10-12	2.75	2.54	2.39	**2.32**	**2.18**	**2.11**	**1.96**
Supply Driven (LB Priority)	< 10	2.75	2.654	2.52	2.35	**2.22**	**2.14**	**1.96**

Alternative (including CCS Comparative Baseline)	Flow Category (maf)	Max	90th percentile	75th percentile	Median	25th percentile	10th percentile	Min
Supply Driven (LB Pro Rata)	> 16	2.59	**2.21**	**2.21**	**2.2**	**2.2**	**2.2**	**2.1**
Supply Driven (LB Pro Rata)	14-16	2.59	2.35	**2.31**	**2.2**	**2.19**	**2.14**	**2.08**
Supply Driven (LB Pro Rata)	12-14	2.75	2.39	2.33	**2.21**	**2.18**	**2.11**	**2.02**
Supply Driven (LB Pro Rata)	10-12	2.75	2.54	2.39	**2.32**	**2.18**	**2.11**	**1.96**
Supply Driven (LB Pro Rata)	< 10	2.75	2.654	2.52	2.35	**2.22**	**2.14**	**1.96**

Note: Ranks in blue are below the historically derived threshold of 2.33. This is the 90th percentile rank from 2008–2024 during the 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.

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 three-year average of Lees Ferry natural flow. The figure visualizes the same data that is included in **Table TA 12-4** 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.

The Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) and Maximum Operational Flexibility Alternative performed almost identically in the Average Flow Category (12.0–14.0 maf), with similar median preservation risk ranks and an interquartile range at or below the 2008–2024 defined threshold. The Enhanced Coordination Alternative had a large median preservation risk, but a similar interquartile range to the other best performing alternatives. The Basic Coordination Alternative performed similarly to the Enhanced Coordination Alternative, but it had greater variability and a larger proportion of its interquartile range above the historically defined threshold. 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 historic 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 historic 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 preservation risk exceeding historic conditions. Under the driest conditions, all alternatives have a moderately strong chance of exceeding historic 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.

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

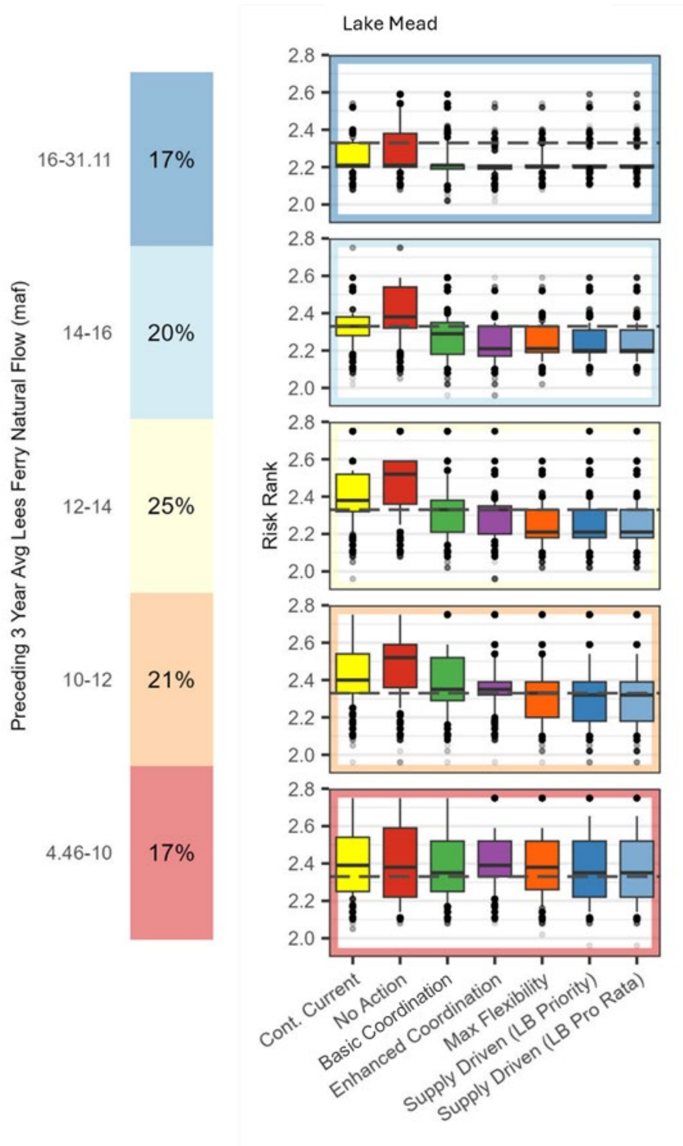
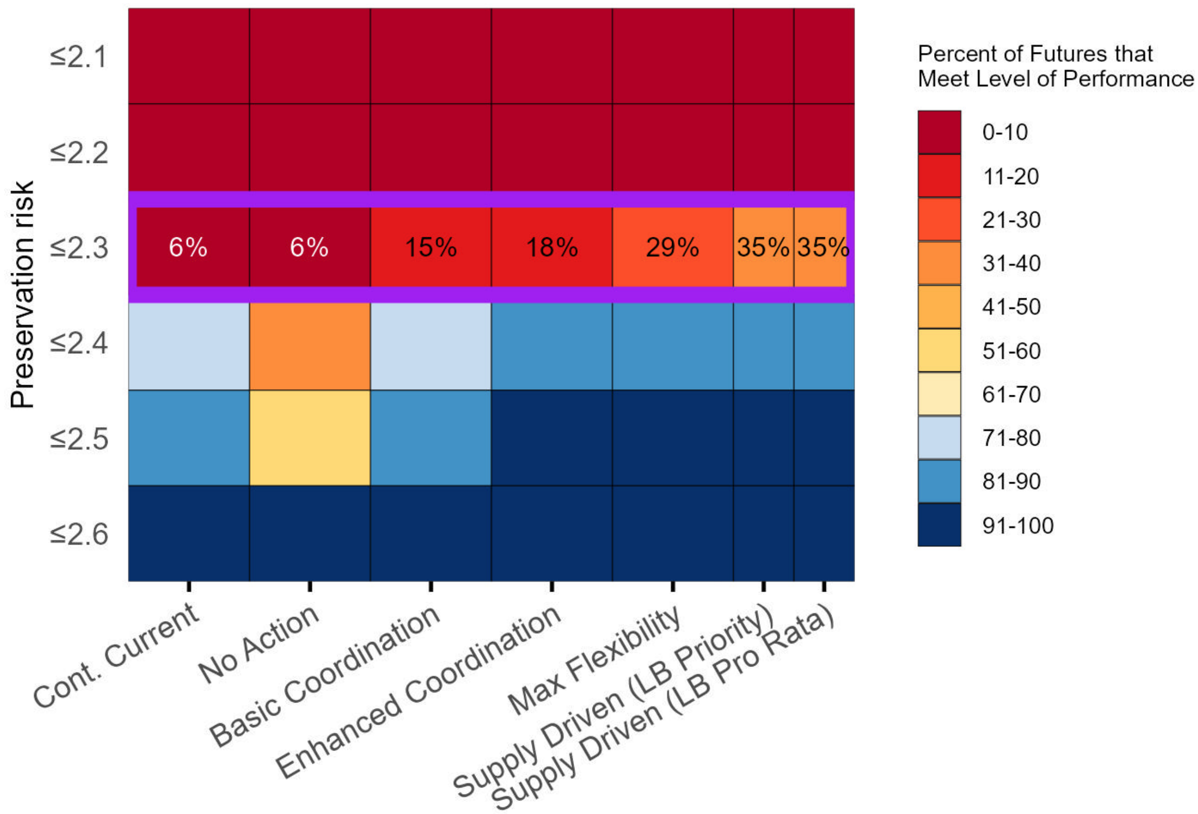


Figure TA 12-8 below depicts the performance of each alternative with respect to keeping paleontological preservation risk ranks at Lake Mead below the historically derived threshold in at least 90 percent of months. This is the same threshold as what was used in **Figure TA 12-7**. The figure is broken 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 sub periods. 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.

Figure TA 12-8
Paleontological Resources in Lake Mead National Recreation Area: Robustness. Percent of futures in which monthly preservation risk stays below the value specified in each row in at least 90% of 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 35 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 29 percent of futures. The No Action Alternative and CCS Comparative Baseline are the least robust and perform identically, succeeding in 6 percent of futures; the Basic Coordination Alternative and Enhanced Coordination Alternative perform similarly (15 percent and 18 percent successful futures).

In lower rows of the heat map, the Enhanced Coordination, Maximum Operational Flexibility, and Supply Driven Alternatives (both LB Priority and LB Pro Rata approaches) begin to perform better at the same rate, consistently achieving 91–100 percent robustness by 2.5. The CCS Comparative Baseline, No Action Alternative, and Basic Coordination Alternative achieve 91–100 percent robustness at 2.6.

Robustness of the alternatives does not immediately improve when analyzing shorter modeling periods. In the 2027–2039 period, robustness of the CCC Comparative Baseline, No Action

Alternative, and action alternatives actually drops; the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) drops more than 10 percent, from 35 percent in the full modeling period to 21 percent in the decadal subperiod.

Robustness quickly improves in the 2040–2049 and 2050–2060 subperiods. The Supply Driven Alternative is the most robust in 2040–2049, with 63 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 and Maximum Operational Flexibility Alternatives reach 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.

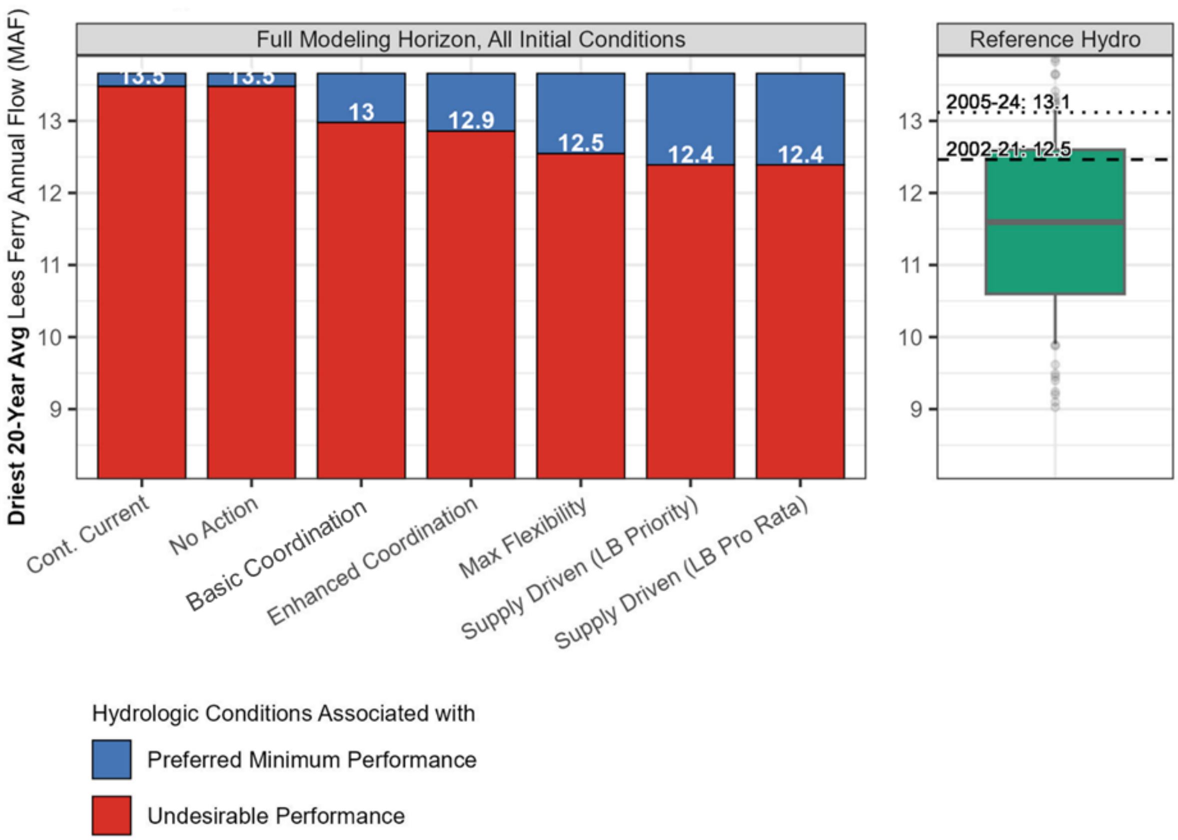
In the 2050–2060 subperiod, the Enhanced Coordination Alternative and Supply Driven Alternative (both LB Priority and LB Pro Rata approaches) reach 91–100 percent robustness at 2.5. At the historically derived threshold, the Maximum Operational Flexibility Alternative is more robust than the Enhanced Coordination Alternative (59 percent and 35 percent, respectively). However, the Enhanced Coordination Alternative is slower 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 61 percent of futures.

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 20-year average Lees Ferry natural flow was identified as a good predictor of undesirable performance; this is shown in the reference hydrology panel. The driest observed 20-year average flow from 2002–2021 (12.5 maf, dashed line) and the average flow from 2005–2024 (13.1 maf, dotted line) are also provided in the reference hydrology for comparison.

Paleontological resources are the most vulnerable to risk under the CCS Comparative Baseline and No Action Alternative. Undesirable performance occurs at 13.5 maf; nearly 100 percent of the reference hydrology traces include average flows of 13.5 maf or lower. These two scenarios are vulnerable to conditions that have already occurred; the 20-year average flow at Lees Ferry from 2002–2021 is 13.1 maf. The Basic Coordination Alternative and Enhanced Coordination Alternative are vulnerable to increased risk to paleontology sites at flows of 13.0 maf and 12.9 maf, respectively.

The Maximum Operational Flexibility Alternative results in undesirable performance if the future includes a 20-year average flow of 12.5 maf, which is the same as the 2002–2021 observed driest flow. Under the Supply Driven Alternative (both LB Priority and LB Pro Rata approaches), paleontological resources become vulnerable to risk at flows of 12.4 maf. Approximately 75 percent of reference hydrology traces are drier than 12.4 maf.

Figure TA 12-9
Paleontological Resources in Lake Mead National Recreation Area: 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

The continual cycle of inundation of paleontological resources is more conducive to preservation than repeated cycles of inundation and exposure and risks of wave action. Changes in lake elevations that may expose previously inundated paleontological resources is the biggest concern; the paleontological preservation risk model utilizes 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, followed by the Maximum Operational Flexibility Alternative. Both alternatives exhibit median risk ranks that are at or below the threshold. The Basic Coordination Alternative was the least effective action alternative with regard to meeting the paleontological preservation risk threshold. This alternative became successful at the Moderately Wet Flow Category but was consistently exceeding the threshold at the Average Flow Category and drier. The No Action Alternative and CCS Comparative Baseline performed 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 performed similarly and produced median preservation risk rank around, or just above, the historically derived threshold in all hydrologic conditions except for the Critically Dry Flow Category. All alternatives exceeded historic preservation risk conditions under the Critically Dry Flow Category.

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 water level fluctuations 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 sand-bar 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.
Percent of futures in which the fraction of sand Mass transported above 37,000 cfs is the value specified in each row

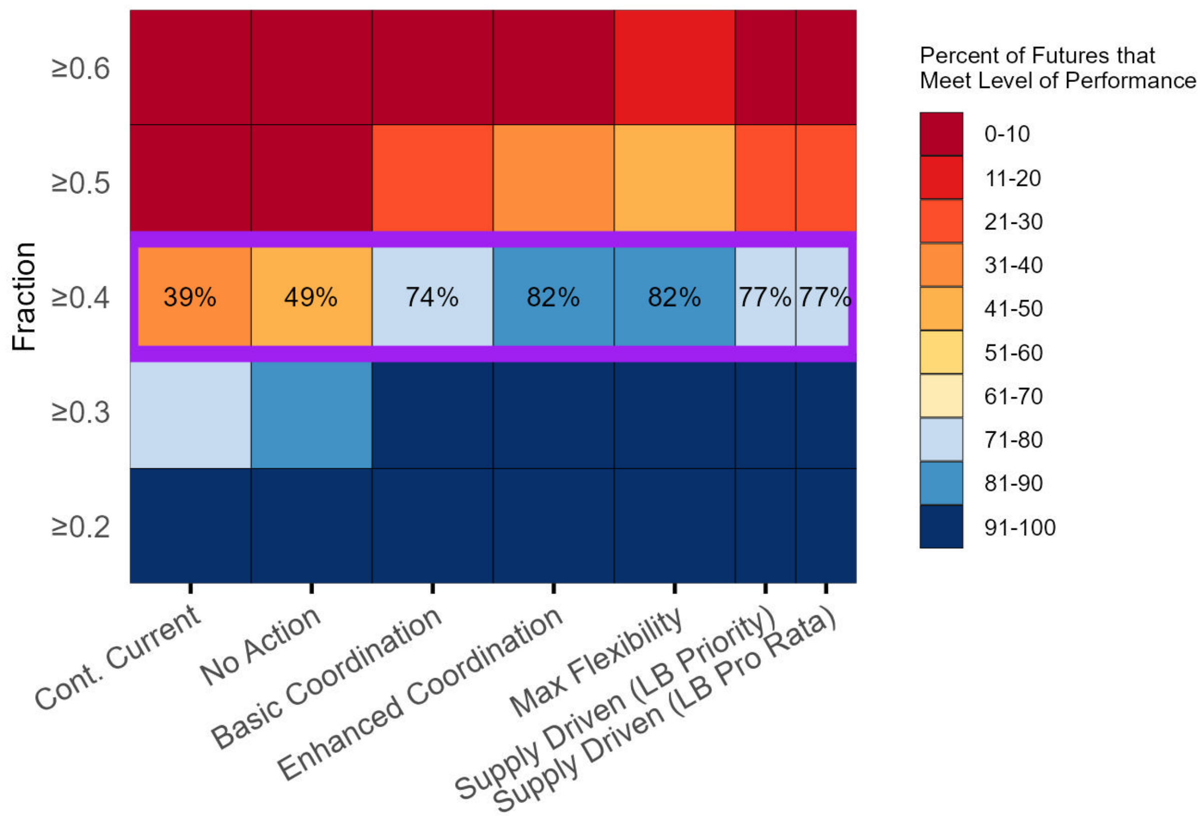


Figure TA 12-10 evaluates how robustly each alternative supports sandbar formation by showing the percentage of futures in which at least 40 percent of total sand mass is transported during sandbar-forming flows. This 40 percent threshold was selected as an indicator of conditions likely to support adequate sand deposition to retain sandbars.

The Enhanced Coordination and Maximum Operational Flexibility Alternatives exhibit the highest robustness, each achieving successful outcomes—defined as meeting or exceeding the 40-percent threshold—in 82 percent of futures. 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 77 percent of futures, while the Basic Coordination Alternative performs moderately lower at 74 percent. Although these three alternatives provide less consistent support for sandbar-forming transport than the two highest-performing action alternatives, they outperform the No Action Alternative and CCS Comparative Baseline.

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 **TA 12.2.1**, *Methodology,* the aeolian transport model looks at favorable conditions for wind-born 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 modelling used is from the Marble Canyon sub-reach from Lee's Ferry to the Little Colorado River. The exposed sand modelling was conducted for the portion of the river from Lee's Ferry to Bright Angel Creek. But the general conclusions are pertinent to the entire river.

The results of the annual vegetation cover modelling are presented in **TA 9**, **Vegetation including Special Status Species**. Overall, less vegetation is better for aeolian sand transport as it leaves sand exposed to be picked up by the wind. As discussed in **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, and HFEs are shorter, vegetation cover increases (see **Figure TA 9-13**).

For the Average Flow Category, vegetation cover under all scenarios would be around observed conditions with the Enhanced Coordination Alternative being the only alternative with vegetation cover under historic conditions. Under the dry and critically dry conditions, vegetation cover increases and differentiation between alternatives can be seen. For the critically dry category, the No Action Alternative has the highest level of vegetation cover (median acreage just under 30 acres), followed by the Supply Driven Alternative (median acreage just under 25 acres). The Basic Coordination, Enhance Coordination, and Maximum Operational Flexibility Alternatives would have the less median acreage of vegetation cover under the critically dry category at about 20 acres.

The results of the sandbar volume modelling are presented in **TA 5**, Geomorphology and Sediment. For the aeolian transport model, increased sandbar volume means more sand available to protect paleontological resources. In general, as conditions get drier and the amount of water flowing through the river decreases, sandbar volume increases (see **TA 5.2.4**, *Issue 4: Sandbar Volume* in **TA 5**, Geomorphology and Sediment). Beginning in the Average Flow Category (see **Figure TA 5-11** in **TA 5**, Geomorphology and Sediment), the Enhanced Coordination and Maximum Operational Flexibility Alternatives outperform the other scenarios in sandbar volume increase with a value at or above median of 1,700 cubic meters for the average through critically dry flow categories. The Basic Coordination and the Supply Driven Alternatives perform similarly in the Average Flow Category but then drop in sandbar volume as conditions become drier.

Figure TA 12-11 shows the results of the water year average of exposed sand area modelling. As with sandbar volume, increased sand area is beneficial for the aeolian transport of sand to protect paleontological resources. Under Average Flow Category, exposed sand area is at or just below the historic median acreage. As conditions become drier, all the modelled scenarios perform similarly with forecasted median exposed sand area above the observed median with the Enhanced Coordination Alternative having a slighter higher median than the action alternatives.

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

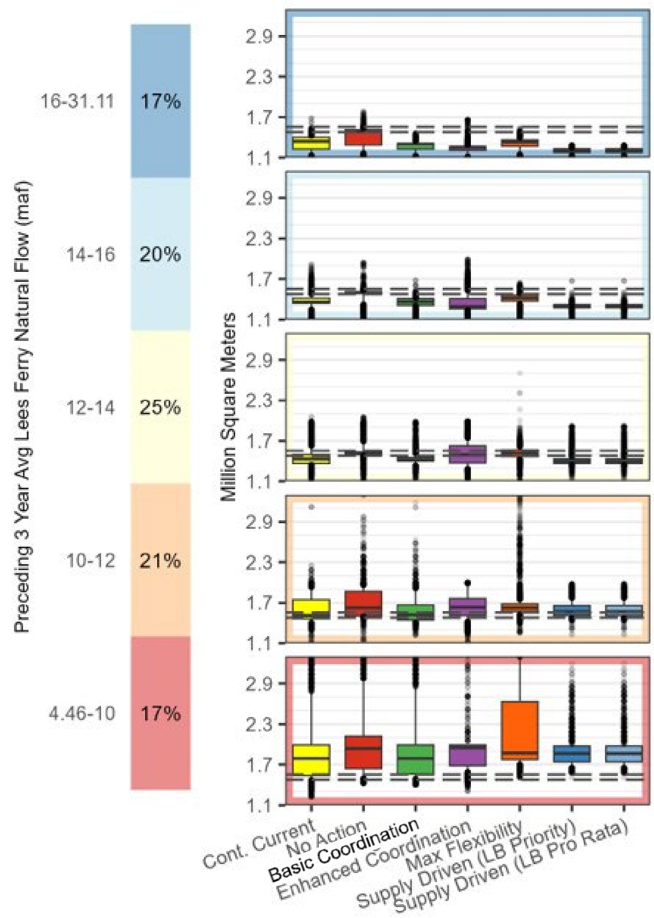


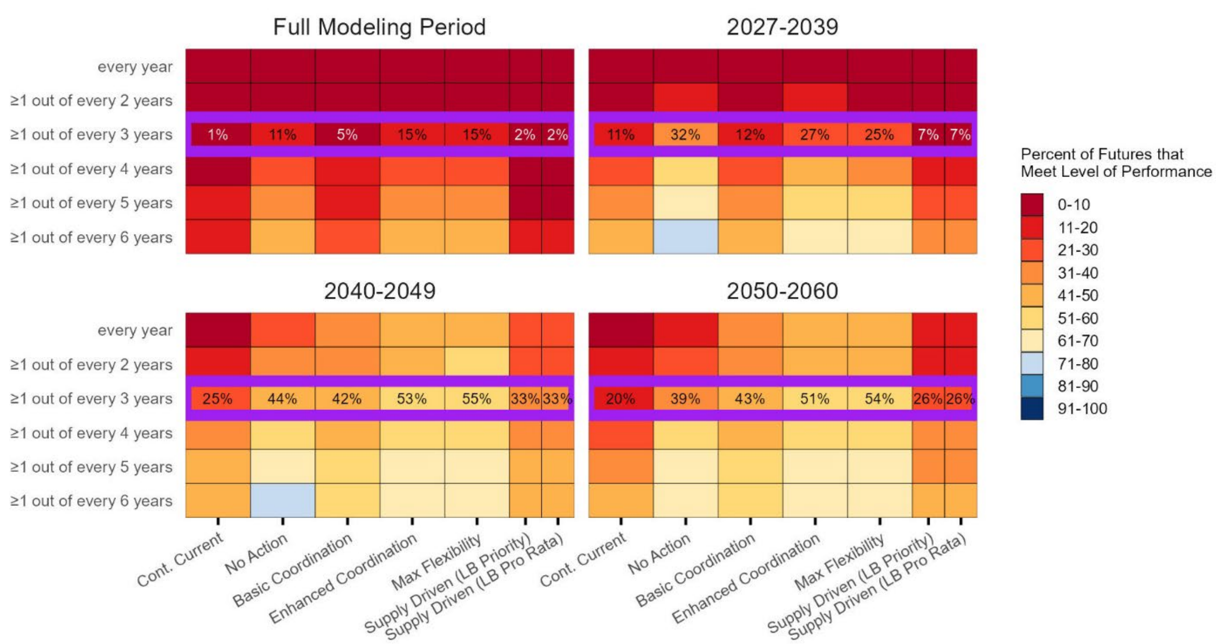
Figure TA 12-12 shows the results of the aeolian sand modelling in which the percent of futures meet one of two criteria: either the annual sand volume is greater than the median observed sand volume over the last 20 years and the vegetation cover area is less than the median observed area over the last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

Over the full modelling period, the Enhanced Coordination and the Maximum Operational Flexibility Alternatives are the most robust meeting the desired conditions of at least one out of every three years in 15 percent of futures followed by the No Action Alternative only in 11 percent of futures. The Supply-Drive Alternative is the least robust, meeting the desired conditions in only

2 percent of futures. If the year interval is lengthened (i.e., to one out of four, five, or six years) the models perform in a similar overall pattern with the Enhanced Coordination and the Maximum Operational Flexibility Alternatives performing the best.

When results are split out over intervals from 2027–2039, 2040–2049, and 2050–2060, the percent of futures meeting the desired conditions increases for both the Enhanced Coordination and the Maximum Operational Flexibility Alternatives from 27 percent to 53 percent and 51 percent and from 25 percent to 55 percent and 54 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 overtime in the modelling with the understanding that HFEs would continue as planned. In reality, the decision to conduct HFEs is dependent on annual review.

Figure TA 12-12
Multi-model Aeolian Transport Condition: Robustness.
Percent of futures in which annual sand area is >50th and vegetation cover is <50th percentile or sandbar volume is >1.5 times initial condition in the frequency specified in each row



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 50 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 15 percent of successful futures for these alternatives, the Basic Coordination Alternative and Supply Driven Alternative produced values of 5 percent or lower.

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 is not anticipated within the river corridor when compared to 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 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 at, 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 87 percent and 82 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 20 percent of futures over the full modeling period. The No Action Alternative is only 71–80 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 29 percent, 25 percent, and 24 percent of futures, respectively.

Alternatives that are more robust at maintaining 3,500 feet elevation at Lake Powell are inherently more robust at inundating paleontological resources below 3,500 feet elevation. Therefore, the risk of human disturbance would be for resources above 3,500 feet. The preservation risk rank historically derived threshold is achieved at approximately 3,500 feet 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 at, 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 80 percent and 79 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 75 percent and 71 percent of futures, respectively.

The No Action Alternative is the least robust, keeping Lake Mead elevation above 975 feet in 100 percent of months in 25 percent of futures over the full modeling period. Robustness of the CCS Comparative Baseline is 45 percent; robustness of the Basic Coordination Alternative is 58 percent.

TA 12.2.5 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-burial cycles can weaken fossil integrity over time.

Under the Maximum Operational Flexibility Alternative, 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.

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.

TA 12.3 Glossary

Fossil	Any remains, trace, or imprint of a plant, animal, or other organism that has been preserved in the geologic record. Fossils can include body fossils (e.g., bones, teeth, shells, leaves), trace fossils (e.g., tracks, trails, burrows, coprolites, chemical signatures), and various kinds of microfossils (e.g., pollen grains, spores, diatoms). Fossils are generally considered to be older than about 11,700 years (the end of the Pleistocene Epoch) but remains older than middle Holocene age (about 5,000 years) can also be considered to represent fossils because they are part of the record of past life.
Paleontology	The study of life in past geologic time based on fossil remains, including their anatomy, phylogeny, ecology, relationships to existing plants, animals, and environments, and the chronology of the Earth's history.

Paleontological Resource	Fossils, fossil localities, and the geologic unit containing fossils or with the potential to contain fossils.

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