APPENDIX A:

ADAPTIVE MANAGEMENT WORKING GROUP DESIRED FUTURE CONDITIONS

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ADAPTIVE MANAGEMENT WORKING GROUP DESIRED FUTURE CONDITIONS

The Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) Draft Environmental Impact Statement (DEIS) joint lead agencies have used the 2012 Glen Canyon Dam Adaptive Management Program (GCDAMP) Desired Future Conditions (DFCs) as a basis for the resource goals and objectives of the DEIS as presented in Section 1.4 of the DEIS. The resource goals and objectives are based on and consistent with the DFCs, but are more concise and direct relative to the LTEMP purpose and need of the proposed action. The following text is based on the document *Desired Future Conditions for the Colorado River Ecosystem in Relation to Glen Canyon Dam* (DFC Ad Hoc Committee 2012).

The DFCs were intended to be used within the GCDAMP to help guide the development of recommendations concerning management of Glen Canyon Dam operations and related activities and dam impacts on Grand Canyon National Park (GCNP) and Glen Canyon National Recreation Area (GCNRA). The DFCs focus on those conditions that can be accomplished through dam operations and also identify those conditions that might be achieved through non-operational measures.

The Secretary of the Interior (the Secretary) is authorized to consider and implement both operational and non-operational measures to address downstream effects of Glen Canyon Dam if those measures meet the Grand Canyon Protection Act’s (GCPA’s) goal of protecting, mitigating adverse impacts on, and improving the resources downstream of the dam. Section 1802 of the GCPA provides the following:

a. *In General*—The Secretary shall operate Glen Canyon Dam in accordance with the additional criteria and operating plans specified in Section 1804 and exercise other authorities under existing law in such a manner as to protect, mitigate adverse impacts on, and improve the values for which GCNP and GCNRA were established, including, but not limited to, natural and cultural resources and visitor use.

b. *Compliance with Existing Law*—The Secretary shall implement this section in a manner fully consistent with and subject to the Colorado River Compact, the Upper Colorado River Basin Compact, the Water Treaty of 1944 with Mexico, the decree of the Supreme Court in Arizona v. California, and the provisions of the Colorado River Storage Project Act of 1956 and the Colorado River Basin Project Act of 1968 that govern allocation, appropriation, development, and exportation of the waters of the Colorado River basin.

c. *Rule of Construction*—Nothing in this title alters the purposes for which the GCNP or the GCNRA were established or affects the authority and

> responsibility of the Secretary with respect to the management and administration of the GCNP and GCNRA, including natural and cultural resources and visitor use, under laws applicable to those areas, including, but not limited to, the Act of August 25, 1916 (39 Stat. 535), as amended and supplemented.

The Bureau of Reclamation (Reclamation) is charged with balancing a complex set of interests in operating the dam. Those interests include not only the endangered species below the dam, but also Tribes in the region, the seven Colorado River basin states, large municipalities that depend on water and power from Glen Canyon Dam, agricultural interests, GCNP, GCNRA, and national energy needs at a time when clean energy production is becoming increasingly important. The DFCs will assist the AMWG in providing recommendations to the Secretary of the Interior for future decision-making. The DFCs have evolved from discussions during the entire 16-year history of the AMWG, and were generated in the following form from the concerted work of the DFC Ad Hoc Group and the federal agency regional leadership during 2010 and 2011.

The vision and mission of the AMWG (adopted on July 21, 1999) was developed to guide adaptive management of Glen Canyon Dam, and helps explain how and why definition of desired conditions is important:

> *The Grand Canyon is a homeland for some, sacred to many, and a national treasure for all. In honor of past generations, and on behalf of those of the present and future, we envision an ecosystem where the resources and natural processes are in harmony under a stewardship worthy of the Grand Canyon.*
>
> *We advise the Secretary of the Interior on how best to protect, mitigate adverse impacts to, and improve the integrity of the Colorado River ecosystem affected by Glen Canyon Dam, including natural biological diversity (emphasizing native biodiversity), traditional cultural properties, spiritual values, and cultural, physical, and recreational resources through the operation of Glen Canyon Dam and other means.*
>
> *We do so in keeping with the federal trust responsibilities to Indian Tribes, in compliance with applicable federal, state, and Tribal laws, including the water delivery obligations of the Law of the River, and with due consideration to the economic value of power resources.*
>
> *This will be accomplished through our long-term partnership utilizing the best available scientific and other information through an adaptive ecosystem management process.*

The DFCs are intended to be statements of qualitative goals and objectives for the GCDAMP, realistic and achievable through the operation of Glen Canyon Dam and related activities, subject to the Law of the River and other laws and authorities and consistent with the GCPA. These DFCs may not be entirely or collectively achievable; there will be tradeoffs and inherent limitations. This fact does not diminish their value. These DFCs of the affected resources have been identified by the stakeholders as appropriate goals for the AMP and are based on information available at this time. As new information develops, the DFCs may need further revision and refinement. Therefore, these DFCs are neither fixed nor final. This is intended to be a "living document" that reflects advances in learning and understanding. This is consistent with the process—and application—of adaptive management.

The Colorado River Ecosystem (CRE) is defined as the Colorado River mainstream corridor and interacting resources in associated riparian and terrace zones, located primarily from the fore bay of Glen Canyon Dam to the western boundary of GCNP. It includes the area where the dam operations impact physical, biological, recreational, cultural, and other resources. The scope of GCDAMP activities may include limited investigations into some tributaries (e.g., the Little Colorado and Paria Rivers).

The majority of the CRE exists within the boundaries of two national parks and proposed wilderness areas. Despite these protections, the CRE could be considered "a human-dominated ecosystem, one whose aesthetic appeal, goods and services, and spiritual services are widely used and appreciated and needed by a broad cross-section of society. Adaptive management of the CRE has been adopted to ensure the sustainability of the natural environment with the least impact on the goods and services the CRE provides to society. As such, and as information about the CRE has increased, its stewardship is moving toward an ecosystem perspective, fully recognizing the role of humans, and this approach is reflected in the structure of this document." (DFC Ad Hoc Committee 2012)

The DFCs are divided into four categories, including the CRE, Power, Cultural Resources, and Recreation. There are many direct, indirect, short-term, and long- term ecosystem responses to dam existence and operations. The DFCs are directly or indirectly linked to each other on short- and long-term bases through dam-related flows, sediment retention and distribution, hydropower production, fish and wildlife populations, recreation, and visitor experience. The following sections are excerpted from the 2012 DFC document.

A.1 DESIRED FUTURE CONDITIONS: COLORADO RIVER ECOSYSTEM

A.1.1 DFC Description

The term "ecosystem" refers to the combined physical and biological components of an environment. An ecosystem is generally an area within the natural environment in which physical (abiotic) factors and processes of the environment, such as geology, climate, and soil development, function along with interdependent (biotic) organisms, such as plants and animals, in the same habitat and create a dynamic and interconnected system. Ecosystems usually encompass a number of food webs. An ecosystem is a functional unit within a given area consisting of living things and the nonliving chemical and physical factors of their environment, linked together through nutrient cycle and energy flow.

A.1.2 DFC Background and Legislation

Glen Canyon Dam has had a profound impact on the aquatic and terrestrial domains of the CRE from lower Lake Powell downstream to Lake Mead. The CRE DFCs are designed to be consistent with the GCPA, Law of the River, and other appropriate laws and mandates. The CRE DFCs apply the requirements of the GCPA, and are the goals that AMWG members will consider when making recommendations to the Secretary.

A.1.3 Why the Colorado River Ecosystem DFCs Are Important

These CRE DFCs address the natural resource values for which the GCNP and the GCNRA were established. The DFCs aim to comply with the GCPA and describe the individual resource objectives sought with the realization that they may not be achievable in the process of finding the most desirable mix of resources in the CRE and the natural habitats, and natural ecosystem processes. Native and nonnative species are to be managed in accord with federal regulations, policies, and guidelines. The CRE described herein includes most of the native natural resources found in the Colorado River. Those resources are managed, consistent with the Law of the River, described in part in Section 1802(b) of the GCPA, under the National Park Service (NPS) Organic Act, the Redwoods Amendment, NPS 2006 Management Policies, the Wilderness Act, the Antiquities Act, the Endangered Species Act (ESA), the GCPA, the Fish and Wildlife Coordination Act, and other federal legislation. The health of the river ecosystem and the protection of the resource values of GCNP and GCNRA are important to the nation, many Native American Tribes, the economy of the Southwest, and the millions of visitors to the parks and the region.

The CRE DFCs will provide a foundation for and help define the components of the Core Monitoring Program under development by the Grand Canyon Monitoring and Research Center (GCMRC). The Core Monitoring Program ultimately will be essential to quantifying, measuring, and reporting the status of the natural resources, allowing the Secretary and the GCDAMP to track progress toward desired outcomes. DFCs will also provide foundation support in the development of other planning and management assignments associated with the GCDAMP.

A.1.4 Colorado River Ecosystem DFCs

A.1.4.1 Sediment-Related Resources DFCs

High-elevation open riparian sediment deposits along the Colorado River in sufficient volume, area, and distribution so as to provide habitat to sustain native biota and desired ecosystem processes include the following:

- Nearshore habitats for native fish,

- Marsh and riparian habitat for fish (food chain maintenance),

- Cultural resource preservation, and

- Maintenance of camping beaches.

A.1.4.2 Water Quality DFCs

Water quality with regard to dissolved oxygen, nutrient concentrations and cycling, turbidity, temperature, and so forth, is sufficient to support natural ecosystem functions, visitor safety, and visitor experience to the extent feasible and consistent with the life history requirements of focal aquatic species including the following:

- Ecosystem-sustaining nutrient distribution, flux, and cycling.

- Hydro-physical conditions and characteristics of the CRE necessary to sustain aquatic biota.

- Acceptable water quality for human health and visitor experience.

A.1.4.3 Colorado River Ecosystem Aquatic Resource DFCs

Aquatic Food Base DFCs

- The aquatic food base will sustainably support viable populations of desired species at all trophic levels.

- Assure that an adequate, diverse, productive aquatic food base exists for fish and other aquatic and terrestrial species that depend on those food resources.

Native Species DFCs

- Native fish species and their habitats (including critical habitats) sustainably maintained throughout in each species' natural ranges in the CRE.

- Healthy, self-sustaining populations of other remaining native fish with appropriate distribution (flannelmouth sucker, bluehead sucker, speckled dace) so that listing under the ESA is not needed.

Humpback Chub DFCs

- Achieve humpback chub recovery in accord with the ESA and the humpback chub comprehensive management plan, and with the assistance of collaborators within and external to the GCDAMP.

- A self-sustaining humpback chub population in its natural range in the CRE.

- An ecologically appropriate habitat for the humpback chub in the mainstem.

- Spawning habitat for humpback chub in the Lower Little Colorado.

- Establish additional humpback chub spawning habitat and spawning aggregations within the CRE, where feasible.

- Adequate survival of young-of-year or juvenile humpback chub that enter the mainstem to maintain reproductive potential of the population and achieve population sizes consistent with recovery goals.

Rainbow Trout DFCs

A high-quality trout fishery in GCNRA, as further described in the Recreation DFC that does not adversely affect the native aquatic community in GCNP:

- Minimize emigration of nonnative fish from the Lees Ferry reach in GCNRA to downstream locations.

- Minimize emigration of nonnative warm water fish to the mainstem Colorado River.

Extirpated Species DFC

Re-establish fishes extirpated from Grand Canyon, where feasible and consistent with recovery goals for humpback chub and the recovery goals of those extirpated fishes. See the linkages that follow for further information.

Nonfish Biotic Communities DFCs

Native non-fish aquatic biota and their habitats are sustainably maintained with ecologically appropriate distributions:

- Populations of native non-fish species (invertebrates and vertebrates, including northern leopard frog).

- GCDAMP support, actions, and funding are limited to incorporation of dam operations that are conducive to restoration of extirpated species.

- Minimize the abundance and distribution of nonnative species in the CRE.

- Sustainable dam-influenced aquatic, wetland, and springs plant communities and associated biological processes, including those supporting threatened and endangered species and their habitats.

A.1.4.4 Colorado River Ecosystem Riparian Resource DFCs

Native riparian systems in various stages of maturity are diverse, healthy, productive, self- sustaining, and ecologically appropriate, as indicated by the following:

- Native, self-sustaining riverine wetlands, and riparian vegetation and habitat, with appropriate mixture of age classes.

- Healthy, self-sustaining populations of native riparian fauna (both resident and migratory).

- Habitat for sensitive species within the CRE.

- Encourage the resolution of the taxonomic status of the Kanab ambersnail (e.g., completely describe the taxa and subspecies).

- Habitat for neotropical migratory birds, waterfowl, and other appropriate native bird species.

- Ecological functions of tributary mouths and riverside springs, including habitat for native species.

A.1.5 Colorado River Ecosystem DFCs Additional Information

A.1.5.1 Colorado River Ecosystem Linkages

Physical characteristics, including climate, site-specific geomorphology, dam-related discharge and flow, and tributary flows, generally predominate over biological processes. The aquatic and riparian components of the CRE are linked to fluvial habitat distribution and the collection, composition, structure, and population dynamics of living organisms. “Lateral” bio-ecological processes, such as competition, and “top-down” processes, such as predation, parasitism, and decomposition, can influence some elements of these linkages over time.

In addition to physical and biological interactions, the CRE is linked to Native American cultural resources such as archeological and cultural properties. Recreation benefits have resulted from both dam operations and healthy ecosystem conditions.

A.1.5.2 Colorado River Ecosystem Metrics

These DFCs are intended to guide the gathering and analysis of data pertinent to the CRE in GCNP and GCNRA. The CRE DFCs and the related documents will be used to provide direction toward development of the core monitoring program under development by the GCMRC. Through diligent and consistent monitoring, GCMRC may inform the Secretary as to whether as to what degree these DFCs are being achieved. Such monitoring may include the following:

- Percentage of critical habitat lost or gained;
- Condition of species variability (native population, abundance, distribution);
- Carrying capacity thresholds; and
- Population estimates.

A.2 POWER DESIRED FUTURE CONDITIONS

A.2.1 Power DFC Description

Hydroelectric power is generated by the release of stored water through Glen Canyon Dam. The dam's eight generators can produce up to 1,320 megawatts: enough electricity to serve 1.3 million residential customers. The integration of hydropower and other resources provides an efficient and flexible operation of this region's electrical resources. Releases of water from Glen Canyon Dam are adjusted in part to follow customer loads.

A.2.2 Power DFC Background and Legislation

Glen Canyon Dam is an important component of the Colorado River Storage Project (CRSP), which stores water, the Western United States' most vital resource, during wet years for use in times of drought, much like a bank account. As part of the nation's critical infrastructure, the water stored by Glen Canyon Dam is vital to the growing water needs of the Western United States. More than 30 million people depend on the water stored behind the dam for drinking, irrigation, and other municipal and industrial uses.

Revenues from the sale of hydropower generation from Glen Canyon Dam and other CRSP facilities are used to repay reimbursable costs and interest on the interest-bearing costs of the federal investment in the CRSP, and are also used to repay over 85% of the irrigation costs of CRSP federal irrigation projects. These revenues are also used, instead of annual federal appropriations, to pay for the yearly operation, maintenance, and replacement costs of Glen Canyon Dam and other CRSP facilities.

The Reclamation Project Act of 1939 provides that hydropower produced by Glen Canyon Dam and other CRSP facilities be offered for sale first to municipalities, other public corporations and cooperatives, and other nonprofit organizations financed in whole or in part by loans made pursuant to the Rural Electrification Act of 1936. Customers include rural electric associations, federal facilities, state agencies, universities, and 57 Native American entities.

A.2.3 Why the Power DFC Is Important

- Hydropower is an authorized purpose of Glen Canyon Dam.

- Hydropower produced by Glen Canyon Dam is under long-term contract to not-for-profit entities and 57 Tribal entities.

- Power revenues are a significant funding source (providing an estimated $20 million/year) for the GCDAMP, Upper Colorado River and San Juan River Endangered Fish Recovery Programs, and the Colorado River Salinity Control Program.

- Hydropower is a renewable resource that is an important component in the Western Electricity Coordinating Council (WECC). Hydropower production is a national objective to help meet the nation's needs for reliable, affordable, and environmentally sustainable electricity.

- Glen Canyon generation has the ability to "ramp up" to meet system reliability obligations that are important when regional power shortages or power/transmission system disruptions occur.

A.2.4 Power DFCs

- Glen Canyon Dam capacity and energy generation is maintained and increased, so as to produce the greatest practicable amount of power and energy, consistent with the other DFCs.

- Ensure continued delivery of Glen Canyon Dam hydropower to the existing customers who have entered into long-term firm power contracts with the Western Area Power Association (WAPA).

- Ensure sufficient and efficient production of Glen Canyon Dam hydropower in order to provide the revenues to support the CRSP facilities and purposes.

- Maintain the operational flexibility (including but not limited to load following capability, ramp rates, and emergency operations allowances) that enable Reclamation and WAPA to meet the system operating and other regulatory requirements of WECC, North American Electric Reliability Corporation, and the Federal Energy Regulatory Commission, as well as emergency operating criteria for safety and human health situations.

- Maximize the environmental benefits of hydropower generation at Glen Canyon Dam.

- Minimize carbon emissions through hydropower generation at Glen Canyon Dam.

A.2.5 Power DFC Additional Information

A.2.5.1 Power Linkages

- Operational changes, including experimentation and management actions, which include changes to volumes; release limitations (minimum and maximum); ramp rates; and hourly, daily, monthly, and seasonal variability, all potentially impact this resource.

- The above-identified parameters could have impacts to the CRE resources as well as recreational and cultural resources, depending on the operational design.

A.2.5.2 Power Metrics

- Valuation (measurement characterization for an average year):
  - Electric generating capacity (MW);
  - Electric generating energy (MWH);
  - Load following capability (MW/hr);
  - Ramp rate capability (MW/hr);
  - CO_2, SO_2, and NO_x emissions (tons);
  - Power plant water consumption (acre-feet); and
  - Costs ($ millions).

A.3 CULTURAL RESOURCES DESIRED FUTURE CONDITIONS

A.3.1 Cultural Resources DFC Description

Preservation and appropriate management of cultural resources are vital at many levels. At the most basic level, cultural resources are our history; they define and reaffirm us, and provide a tangible record of who we are and where we have been. Their importance may be to the nation as a whole, to a local community, or to a group traditionally associated with the area. This includes resources within the Grand Canyon region, such as resources along the river corridor in Glen and Grand Canyons.

A.3.2 DFC Background and Legislation

Recognition of the importance of cultural resources is codified through numerous statutes and executive orders that mandate protection, consideration, and preservation of cultural resources. Because of the structure of federal law, particularly the National Historic Preservation Act of 1966 (NHPA), cultural resources will be considered below in two broad groupings: (1) those that fall within the purview of the NHPA (*National Register of Historic Places* [NRHP] eligible historic properties); and (2) all other resources of traditional cultural importance. This is done for purely pragmatic reasons; there are specific legal requirements for cultural resources that fall under the NHPA umbrella that do not apply to the second class of cultural resources. The Cultural Resources DFCs apply the requirements of the Grand Canyon Projection Act to "protect, mitigate adverse impacts to, and improve the values for which GCNP and Grand Canyon National Recreation Area (GCNRA) were established," including cultural resources, and are the goals that AMWG members will consider when making recommendations to the Secretary.

A.3.3 Why the Cultural Resources DFCs Are Important

The cultural resources of the Grand Canyon provide a record of human history in the area. They also encompass the traditional cultural use and significance of the Grand Canyon. Maintaining these resources is important to the nation as a whole so we can better understand the long history of the people who came before us and to the traditional groups that consider this area to have traditional significance to them. A number of Native American groups believe the Grand Canyon is their place of origin. These DFCs will help to maintain compliance with relevant cultural resource laws, maintain traditional cultural linkage with the Grand Canyon, and maintain traditional cultural access to and use of resources in the Grand Canyon in accordance with applicable law.

A.3.4 NRHP Eligible (or Potentially Eligible) Historic Properties DFCs

These resources are historic properties that are eligible or potentially eligible for inclusion in the NRHP. The criteria for inclusion are defined in the NHPA, and are described in more detail in *National Register* Bulletins 15 and 38. Resources in the Grand Canyon include the following:

- Prehistoric archaeological sites (including trails, petroglyphs, and pictographs);

- Historic sites (boats, mining, European exploration, river running); and

- Traditional Cultural Properties—for the Grand Canyon, these include:
  - Archaeological sites,
  - Traditional resource use areas,
  - Sacred sites,
  - Landmarks/geographic features,
  - Springs,
  - The Colorado River,
  - Ethno-ecological resources,
  - Significant event locations, and
  - The Grand Canyon itself.

A.3.4.1 Prehistoric Archaeological Sites and Historic Sites

To the extent feasible, maintain significance and integrity through preservation in place:

- If preservation in place is not feasible or reasonable, then implementation of appropriate preservation treatments will be implemented to ensure reduction or elimination of threats consistent with NPS management policies, Tribal traditional values, and historic preservation law.

- Public access to historic properties on Tribal lands is managed by the respective Tribes. On lands administered by the NPS, access to some sites for users of the river corridor is maintained as long as integrity of the sites is not compromised.

A.3.4.2 Traditional Cultural Properties (TCPs)

- Attributes are maintained; for example, NRHP eligibility is not compromised. These attributes will be specific to traditionally associated peoples and will need to be identified by the federal agencies in consultation with those groups. Attributes may include aspects of location or physical integrity, and may be intangible elements that link the resource to ongoing traditional cultural practices.

- The ability of traditionally associated people to maintain access to and use of the resources is preserved, in accordance with applicable law.

- Culturally appropriate conditions of resources are maintained based on traditional ecological knowledge; integration of the desired condition is included in relevant monitoring and management programs.

- Maintain ongoing consultation with the groups for whom the resource has traditional value. Because the desired condition of a TCP needs to be determined by the group for whom it has the traditional value, ongoing consultation is necessary to assess the condition of the resource.

- Mitigate impacts that affect the integrity of the TCPs. How and if effects can be mitigated will need to be determined in conjunction with the traditionally associated peoples for whom the resource holds value.

A.3.5 NRHP Eligible (or Potentially Eligible) Historic Properties DFC Additional Information

A.3.5.1 NRHP Eligible (or Potentially Eligible) Historic Properties Linkages

The goals for the following all have the potential to directly or indirectly affect the condition of the NRHP eligible properties (including some examples of effects):

- Flow
  - Direct inundation
  - Levels of sediment deposition
  - Fluctuation frequency and range

- Sediment
  - Distribution (laterally and vertically)

- Vegetation
  - Species composition
  - Density

- Recreation
  - Camping locations
  - Recreational visitation
  - Trailing

In addition, management and research actions have the potential to directly or indirectly impact these resources.

A.3.5.2 NRHP Eligible (or Potentially Eligible) Historic Properties Metrics

- Erosion (or deposition) rates of substrates in which the sites are contained, and
- Impacts at sites that will affect eligibility.

A.3.6 Resources of Traditional Cultural Significance but Not NRHP Eligible

These are resources of cultural significance to traditional peoples, often Native American Tribes, that do not meet some aspect for eligibility for inclusion in the NRHP. A common reason that a resource does not meet NRHP eligibility requirements is that the resource lacks a clearly defined boundary or does not remain in a fixed location.

Resources that have the potential to be considered of traditional cultural significance in the Grand Canyon include the following:

- Animal resources,
- Geologic materials,
- Landscapes,
- Plant resources,
- Soundscapes,
- Viewscapes, and
- Water.

A.3.7 Resources of Traditional Cultural Significance DFCs

- Maintain the ability of traditionally associated peoples to access and use the resource in accordance with applicable law.
- Maintain culturally appropriate resource conditions based on traditional ecological knowledge and integrate this desired condition into monitoring and management programs.

- Maintain effective consultation with the groups for whom the resource has traditional cultural significance.

A.3.8 Resources of Traditional Cultural Significance Linkages

The goals for the following resources all directly or indirectly affect the condition of resources with traditional cultural significance:

- Flow,
- Sediment,
- Vegetation, and
- Recreation.

In addition, management and research actions have the potential to directly impact these resources.

A.3.9 Resources of Traditional Cultural Significance Metrics

Because culture defines the roles resources play in that culture, only members of that culture can assess the status or health of the resources. Therefore, measures for resource status or health and appropriate management will need to be determined individually by federal agencies in consultation with the traditionally associated peoples.

A.4 RECREATION DESIRED FUTURE CONDITIONS

A.4.1 Recreation DFC Description

The Recreation DFCs are meant to describe goals and objectives for human use of the CRE through GCNRA and the GCNP. They are intended to include not only traditional recreational activities such as whitewater rafting, camping, and fishing, but also such things as educational activities, spiritual engagement, and other appropriate activities and values. Grand Canyon and Glen Canyon offer many ways for people to experience, appreciate, and learn from them, even to those who never visit in person.

A.4.2 DFC Background and Legislation

Recreational use on the Colorado River began before there were any dams there, although its exact beginnings are unknown. Recreational and other activities and values in the Grand

Canyon and Glen Canyon have increased greatly since the construction of Glen Canyon Dam. The Recreation DFC applies the requirements of the GCPA to "protect, mitigate adverse impacts to, and improve the values for which GCNP and Grand Canyon National Recreation Area (GCNRA) were established," including visitor use/recreation, and the goals that AMWG members will consider when making recommendations to the Secretary.

A.4.3 Why the Recreation DFC Is Important

A.4.3.1 Grand Canyon National Park

The Grand Canyon is a unique place in the world. Its natural beauty, challenging environment, fascinating history, wilderness character, biodiversity, and sheer size offer a rare and valuable experience. The river corridor is at the heart of the Grand Canyon. The river corridor and the canyon are worthy of the greatest possible respect, treatment, and protection that can be afforded them. They must be kept vital and intact for future generations.

A.4.3.2 Glen Canyon National Recreation Area

The river corridor through the GCNRA provides opportunity to enjoy outdoor beauty with relatively easy access. It supports a valuable and high-quality trout fishery and offers excellent outdoor opportunities that are more accessible and less demanding than those of the Grand Canyon. It is deserving of respect and protection, while also providing the recreational opportunities for which it was established.

A.4.4 Recreation DFCs

The recreation DFCs have been divided in to four subcategories, each corresponding to a different section of the overall ecosystem or type of use.

A.4.4.1 River Recreation in Grand Canyon National Park

- Stewardship worthy of the Grand Canyon so that it can be passed from generation to generation in as natural a condition as possible.

- Provide maximum opportunity to experience the wilderness character of the canyon.

- Wilderness experiences and benefits available in the canyon include solitude, connection to nature, personal contemplation, joy, excitement, the natural sounds and quiet of the desert and river, and extended time periods in a unique environment outside the trappings of civilization.

- A river corridor landscape that matches natural conditions as closely as possible, including extensive beaches and abundant driftwood.

- A river corridor ecosystem that matches the natural conditions as closely as possible, including a biotic community dominated in most instances by native species.

- A dynamic river ecosystem characterized by ecological patterns and processes within their range of natural variability.

- Numerous campable sandbars distributed throughout the canyon.

- Recreational and wilderness experiences minimally affected by research and management activities.

- River flows that continue to be within a range that is reasonably safe, given the inherent risks involved in river recreation.

A.4.4.2 River Recreation in Glen Canyon National Recreation Area

- A quality recreation experience in Glen Canyon.

- Camping beaches suitable for recreational use.

- A setting and ecosystem that is as close to natural conditions as possible.

- Quality river running and angling recreation opportunities.

A.4.4.3 Blue Ribbon Trout Fishery in Glen Canyon National Recreation Area

- A high-quality sustainable recreational trout fishery in the river corridor in GCNRA, while minimizing emigration of nonnative fishes.

- Operate Glen Canyon Dam to achieve the greatest benefit to the trout fishery in GCNRA without causing excessive detriment to other resources.

A.4.4.4 River Corridor Stewardship

- Management of Glen Canyon Dam that is significantly driven by concern for the cultural values and ecological integrity of the river corridor through the Grand Canyon, with preservation and protection considered over the long term (multiple generations).

- A well-informed public, confident that high-quality scientific information is being used for best stewardship practices in the CRE.

A.4.5 Recreation DFC Additional Information

A.4.6 Recreation Linkages

- A natural, healthy, and protected ecosystem is a fundamentally key element to the recreation experience and wilderness character of the river corridor.

- Cultural resources within and near the river corridor:
  - The history of human habitation and use is an important part of the recreation experience. Individual sites are valuable whether they are open for visitation or designated off-limits.
  - Outfitters and guiding opportunities.
  - Local businesses.

A.4.7 Recreation Metrics

- Socioeconomic value of river recreation in GCNP.

- Socioeconomic value of the river corridor visitation and the Grand Canyon itself, as a whole.

- Economic effects of Grand Canyon tourism.

- Factors that make up the “wilderness character” of the river corridor.

- Number and size of campable beaches, safe flows for an optimal recreation experience.

- Socioeconomic value of river recreation in GCNRA.

- Socioeconomic value of the river corridor itself in GCNRA.

- Socioeconomic value of the fishery in GCNRA.

- Effect of the trout on the ecosystem in GCNP and the social and economic costs of mitigation.

- Characteristics most valued for the fishery; for example, the number, condition, and size of fish, and the ease or challenge of catching them.

- River running visitation metrics.

- Water quality variables that influence river recreation.

- Other river running safety issues.

A.5 REFERENCE

DFC Ad Hoc Committee, 2012, *Desired Future Conditions for the Colorado River Ecosystem in Relation to Glen Canyon Dam.* Available at http://www.usbr.gov/uc/rm/amp/amwg/pdfs/recltr_12April30.pdf. Accessed July 24, 2015.

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APPENDIX B:

PERFORMANCE METRICS USED TO EVALUATE ALTERNATIVES

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APPENDIX B:

PERFORMANCE METRICS USED TO EVALUATE ALTERNATIVES

This appendix describes a set of scientifically based performance metrics that were used by the Draft Environmental Impact Statement (DEIS) team to evaluate the impacts of alternatives on key resources in the Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) DEIS. The metrics were also used in a structured decision analysis process to objectively evaluate how alternatives perform relative to stakeholder values and in the face of critical uncertainties (Appendix C). The metrics were developed in a series of workshops among subject matter experts working on the LTEMP DEIS and were revised to incorporate feedback from Cooperating Agencies and other stakeholders. The performance metrics are intended to be objective measures of the performance of alternatives relative to goals for each affected resource evaluated in the DEIS.

Evaluation of these metrics represents only a component of the impact analysis performed for the DEIS. Other sources of both quantitative and qualitative information, in addition to the metrics described below, were used to assess the overall and relative performance of alternatives and their constituent elements.

The affected resources, associated goals, and performance metrics are described below.

B.1 AQUATIC ECOLOGY

B.1.1 Humpback Chub

Resource Goal: Meet humpback chub recovery goals including maintaining a self-sustaining population, spawning habitat and aggregations in its natural range in the Colorado River and its tributaries below the Glen Canyon Dam.

Performance Metrics

- **Number of Adult Humpback Chub.** This metric provides the estimated number of adult (200 mm+) humpback chub in the Little Colorado River population over the LTEMP period relative to the estimated adult population size in September 2011.

  The modeled number of humpback chub adults was calculated using a size-structured model that considers both the Little Colorado River and mainstem components of the Little Colorado River aggregation and used empirically derived estimates of growth and survival that differ for these two areas. In addition, the size structure of the modeled humpback chub population at the end of the 20-year traces was compared to evaluate possible differences among alternatives. Growth and survival rates in the mainstem are based on inputs related to monthly water temperature for each of the Colorado River Simulation System (CRSS) traces (modeled using the Wright et al. 2008 model) and estimated annual trout abundance in the Little Colorado River reach occupied by humpback chub. Trout abundance was estimated using a trout emigration submodel that models the numbers of trout that leave the Glen Canyon reach (see description of trout fishery metrics below) and subsequently pass through Marble Canyon to the Little Colorado River reach.

- **Potential for Self-Sustaining Aggregations of Humpback Chub.** The potential for a self-sustaining aggregation of humpback chub to be supported at each of eight locations (RM30, 61 [Little Colorado River], 88, 108, 119, 125–128, 157, 213) was based on the output of a temperature suitability model that considers how well water temperatures under a particular alternative meet temperature requirements for important humpback chub life history aspects (spawning, egg incubation, and growth) at each aggregation area. It was assumed that mainstem spawning and egg incubation would be required to support self-sustaining aggregations at each location except for the aggregation at the confluence of the mainstem and the Little Colorado River (RM 61), where successful tributary spawning is known to occur. At each location, the potential for successful spawning, egg incubation, and rearing for juvenile humpback chub at various temperatures was calculated using triangular probability functions based on the reported ranges of suitable temperatures and the reported optimal temperatures for each life history need as presented in Valdez and Speas (2007). A temperature suitability score for each life history need was generated for each day of the modeled LTEMP period using modeled predictions of water temperatures for the aggregation location (modeled using the Wright et al. 2008 model).

  Annual mean temperature suitability scores for each life history need were calculated by averaging daily suitability scores that occur during the appropriate portion of each water year (i.e., April–June for spawning and egg incubation and year-round for growth). The annual potential for an aggregation to be self-sustaining at a particular location was calculated as the geometric mean of the annual temperature suitability scores for each life history event within a particular water year (a value between 0 and 1), and the overall means of the annual scores for each hydrologic trace was used to statistically compare the potential for self-sustaining aggregations to be supported by the various alternatives.

  For each hydrologic trace, the number of aggregation locations where the estimated annual temperature suitability score is $\geq$0.5 was determined for each alternative. The mean number of aggregations with temperature suitability values $\geq$0.5 for all traces was used as an indicator of overall humpback chub temperature suitability for each alternative.

B.1.2 Other Native Fish

Resource Goal: Maintain self-sustaining native fish species populations and their habitats in their natural ranges on the Colorado River and its tributaries.

Performance Metrics

- **Temperature Suitability for Warmwater Native Fish.** The potential for self-sustaining populations of native warmwater fish (other than humpback chub) to be supported at each of five locations (RM 15, 0, 61, 157, and 225) was based upon the output of a temperature suitability model (similar to the modeling approach for humpback chub aggregation evaluations) that evaluates the suitability of water temperatures under a particular long-term (e.g., 20 years) operational regime for meeting identified needs for major life history aspects (spawning, egg incubation, and growth) of a group of native fish species. The model generates individual temperature suitability scores for four species of native fish (flannelmouth sucker, bluehead sucker, razorback sucker, and speckled dace) at each location. Modeled monthly temperatures at different locations under different alternatives (modeled using the Wright et al. 2008 model) were the primary input needed to generate the temperature suitability scores for this metric.

  The relative suitability of conditions under each alternative to support native fish was represented by the mean of the temperature suitability scores for these four species, calculated for each location and also by an overall metric for each alternative that combined the temperature suitability scores for the four species at all locations.

B.1.3 Trout Fishery

Resource Goal: Achieve a healthy high-quality recreational trout fishery in Glen Canyon National Recreation Area and reduce or eliminate downstream trout migration consistent with National Park Service fish management and ESA compliance.

Performance Metrics

- **Lees Ferry Trout Abundance Index.** For age 1+ fish.

- **Catch Rate Index (number/hr).** For age 2+ fish.

- **Emigration Estimate.** Number of age-0 trout moving into Marble Canyon from Glen Canyon.

- **Number of Trout >16 in. Total Length.** These metrics were estimated using a trout-humpback chub model developed specifically for the LTEMP DEIS by

Lew Coggins (U.S. Fish and Wildlife Service), Josh Korman (Ecometrics), and Charles Yackulic (Grand Canyon Monitoring and Research Center). The model uses inputs related to annual water volumes, water temperatures, and specifics of the release patterns (e.g., occurrence of high-flow experiments [HFEs], implementation of trout management flows, amount of daily flow fluctuation) to estimate recruitment and survival of trout within the Glen Canyon reach. Emigration of trout into Marble Canyon was based on statistical relationships to the abundance of trout in Glen Canyon. Size structure of trout within the Glen Canyon reach was modeled for age 1+ trout and the calculated number of trout that exceed 16 in. total length was calculated as an estimate of the quality of the fishery. Angling catch rate was calculated for age 2+ trout based on estimated vulnerability of different age classes.

B.1.4 Nonnative Aquatic Species

Resource Goal: Minimize or reduce presence and expansion of aquatic nonnative invasive species.

Performance Metrics

- **Potential for Establishment and Expansion of Nonnative Fish.** The potential for self-sustaining populations of nonnative warmwater and coldwater fish to be supported at each of five locations (RM –15, 0, 61, 157, and 225) was based upon the output of a temperature suitability model that considers how well water temperatures under a particular alternative meet identified needs for required life history aspects (spawning, egg incubation, and growth) of warmwater and coldwater groups of nonnative fish species. The model generates individual temperature suitability scores for four species of warmwater nonnative fish (channel catfish, green sunfish, smallmouth bass, and striped bass) and two species of coldwater fish (brown trout and rainbow trout) at each location.

  The relative suitability of temperature conditions under each alternative to support the two groups of nonnative fish was represented by the mean of the temperature suitability scores for the species within the groups, calculated for each location and also by an overall metric composed of the temperature suitability scores for the groups at all locations. Modeled monthly temperatures at different locations under different alternatives (modeled using the Wright et al. 2008 model) were the primary input needed to generate the temperature suitability scores for this metric.

- **Potential for Establishment and Expansion of Aquatic Parasites.** A similar temperature suitability model was used to evaluate temperature suitability for the selected fish parasite species (Asian tapeworm, anchor worm, trout nematode, and whirling disease) based on the suitability of specific temperatures to meet the requirements for host species activity and the development of infestations at each of five locations (RM 15, 0, 61, 157, and 225). As with the nonnative fish modeling, temperature suitability for the parasite species under each alternative was evaluated for the five identified locations using modeled water temperature regimes.

The relative suitability of temperature conditions under each alternative to support the parasite species was represented by the mean of the temperature suitability scores for the species group, calculated for each location and also by an overall metric composed of the temperature suitability scores for the group at all locations.

B.2 ARCHAEOLOGICAL AND CULTURAL RESOURCES

Resource Goal: Maintain the integrity of potentially affected *National Register of Historic Places* eligible or listed historic properties in place, where possible, with preservation methods employed on a site specific basis.

Performance Metrics

- **Wind Transport of Sediment Index.** This metric evaluated the availability of fine sediment for wind transport and potential deposition on historic properties at higher elevations (i.e., those properties located at stages above 45,000 cfs). Deposited sediment would serve to protect those resources from erosion. Optimal conditions for wind transport of sediment occur when (1) there is deposition of fine sediment by flows above the stage of normal operations, which represents the availability of sand at higher elevations and (2) there are low flows which expose more sand during the windy season, which would make more dry sand available for redistribution by the wind. This criterion accounts for the two processes using the equation:

$$Wind\ Transport\ Index = FF \times SLI$$

where *FF* is the flow factor and *SLI* is the Sand Load Index produced by the Sand Budget Model.

The flow factor represents the relative amount of exposure of sand deposits on a 0–1 scale that occurs for each day of the windy period (March–June). The daily flow factor was calculated as follows:

FF = 1 for maximum daily flows less than or equal to 8,000 cfs, indicating maximum exposure of sand to wind transport;

FF = 0 for maximum daily flows greater than 31,500 cfs, indicating minimum exposure of sand to wind transport;

FF = 1.34 – (0.00004255×maximum daily flow), for flows between 8,000 and 31,500 cfs. This equation represents the linear decrease in flow factor from 1 at flows of 8,000 cfs to 0 for flows of 31,500 cfs.

The yearly flow factor was calculated by averaging the daily flow factors for the March–June period.

The *SLI* is the ratio of the cumulative sand load transported by high flows (i.e., flows >31,500 cfs) to total cumulative sand load transported by all flows for the alternative (range 0–1; higher index indicates greater likelihood of sediment deposition for wind transport).

Wind Transport Index is a value of 0–1, where a value of 1 has the most exposure to possible movement of sediment by the wind and is therefore the most desirable.

The mean annual Wind Transport Index value for the 20-year modeling period was used as the performance metric for each alternative.

The metric reflects when alternatives create the conditions for movement of sediment by wind, and therefore the potential for cultural resources to be protected, under each alternative. Although wind-blown sand deposited from sandbars created by dam operations may provide some benefit to archaeological site preservation in Grand Canyon, both the extent to which this occurs and the extent to which wind-deposited sand provides long-term preservation of archaeological sites are not known.

- **Flow Effects on Historic Properties in Glen Canyon Index.** Within Glen Canyon, there is concern that significant archeological sites could be negatively affected by flow levels of certain magnitudes.

  Ninemile Terrace, which is considered representative of other archeological sites situated on terraces within Glen Canyon, is potentially affected by higher flows, which inundate and could erode the slope of the terrace. The toe of the slope begins to be inundated at flows above 23,200 cfs. Consequently, the flow metric is calculated as the mean number of days/year the maximum daily flow is greater than 23,200 cfs.

- **Time Off River Index.** In the Grand Canyon, higher flow levels increase the potential for discretionary time off the river for visitors. There is concern that there may be a greater potential for archaeological sites to be visited and possibly affected, if visitors have more time to explore during the day because of increased travel rates at higher flows.

  The calculated index is a yearly value ranging from 0 to 1, where 1 indicates the most potential for discretionary time for visitors (and the highest potential for increased visitation of archaeological sites).

  Calculation of the index involved computing mean daily flow from the hourly flow data and using this value to calculate an off river flow factor. The off river flow factor (ORFF) was calculated as follows:

  – *ORFF* = 0 for mean daily flows less than or equal to 10,000 cfs, indicating the increased time visitors would spend on the river.

  – *ORFF* = 1 for mean daily flows greater than 31,500 cfs, indicating faster river travel times and potentially increased time spent off the river.

  – *ORFF* = (0.0000465× mean daily flow) – 0.465, for flows between 10,000 and 31,500 cfs. This equation represents the linear increase in the metric from 0 at flows of 10,000 cfs (lease negative effect) to 1 for flows of 31,500 cfs (greatest negative effect). Flows greater than 31,500 cfs are assigned flow metric values of 1 because of the increased potential for visitation of cultural sites that occur at elevations above normal operating flows.

  ORFF values for each season were summed and weighted to reflect the uneven use of the river throughout the year; 0.15 for winter months (Nov., Dec., Jan., Feb.), 0.31 for spring and fall months (Mar, Apr, Sep, Oct), and 0.54 for summer months (May, June, July, Aug.) and normalized by the number of days in each season as shown in the following equation.

$$TOR = \{0.15\left(\frac{\sum_{winter} ORFF}{\sum Days_{winter}}\right) + 0.31\left(\frac{\sum_{\frac{spring}{fall}} ORFF}{\sum Days_{\frac{spring}{fall}}}\right) + 0.54\left(\frac{\sum_{summer} ORFF}{\sum Days_{summer}}\right)\}$$

B.3 HYDROPOWER AND ENERGY

Resource Goal: Maintain or increase Glen Canyon Dam electric energy generation, load following capability and ramp rate capability, and minimize emissions, and costs to the greatest extent practicable consistent with improvement and long-term sustainability of downstream resources.

Performance Metrics

- **Combined Value of Hydropower ($).** This composite performance metric combined (1) the value of energy production, (2) the value of capacity, and (3) the value of operational flexibility, to provide a mean annual and total value estimate for Glen Canyon Dam hydropower under each of the alternatives. Performance metrics were developed that quantify the potential value of hydropower production under the limitations imposed by each alternative. These components were estimated using the GTMax-Lite power systems modeling and post-processing analysis, based on monthly and hourly release estimates for the LTEMP period:

  – **Value of Energy Production ($).** Results show mean annual and total quantities of energy production (MWh) and corresponding energy values ($), based on market price estimates ($/MWh) for the time periods generated. (Market price estimates were used to characterize the economic value of energy delivered to the grid.) This metric was obtained directly from GTMax-Lite hourly results and market price estimates.

  – **Value of Capacity ($).** Results show mean annual and total quantities of capacity available (MW) and corresponding capacity values ($), based on market price estimates ($/MW) for the relevant time periods. This metric, derived from GTMax-Lite results and market price estimates, represents an initial proxy for detailed capacity replacement analyses completed in other stages of the LTEMP analysis.

B.4 NATURAL PROCESSES

Resource Goal: Restore, to the extent practicable, ecological patterns and processes within their range of natural variability, including the natural abundance, diversity, and genetic and ecological integrity of the plant and animal species native to those ecosystems.

This resource goal incorporates many different physical and biological processes and ecological components of the river system. As a consequence, the goal does not lend itself to expression in a quantitative metric. Instead of a quantitative metric, alternatives were compared in the DEIS by qualitatively evaluating each alternative's performance relative to this goal considering impacts on various natural processes such as flow, sediment transport, water temperature, riparian vegetation, aquatic organisms, and terrestrial wildlife. This resource goal was not included in the structured decision analysis process.

B.5 RECREATIONAL EXPERIENCE

Resource Goal: Maintain and improve the quality of recreational experiences for the users of the Colorado River ecosystem. Recreation includes, but is not limited to, flatwater and whitewater boating, river corridor camping, and angling in Glen Canyon.

B.5.1 Grand Canyon Metrics

- **Camping Area Index.** It is important to develop and retain adequate medium (16–25 people) and large (>25 people) campsites to meet the visitor capacities established in the National Park Service (NPS) Colorado River Management Plan. The availability of camping area above the stage of normal operations (25,000 cfs) is considered as part of the index.

  Camping area and campsite size are a function of the amount of sand deposited and retained. The output from the Sand Load Index, which simulates sediment conditions between RM 0 and 61 provides a proxy for indicating whether the alternatives are likely to create the conditions conducive to creating/retaining adequate campsite area.

  Camping area and campsite size also are a function of flow level. Lower flows provide more camping area (i.e. there is more camping area at 8,000 cfs than at 25,000 cfs.

  The index was calculated as follows:

  $$Camping\ Area\ Index = SLI \times SWFF$$

  where *SLI* is the Sand Load Index and *SWFF* is the seasonally weighted flow factor.

  SLI is a ratio of the cumulative sand load transported by high flows (i.e., flows >31,500 cfs) to the total cumulative sand load transported by all flows for an alternative (range 0–1; higher index indicates greater likelihood of sediment deposition for campsites).

  SWFF consists of a seasonal weighting (*SW*) and a flow factor (*FF*) component.

  SW is as follows: 0.15 for winter months (Nov., Dec., Jan., Feb.); 0.31 for spring and fall months (March, April, Sept., Oct.), and 0.54 for summer months (May, June, July, Aug.).

  FF is as follows: 1 for daily maximum flows that are less than or equal to 8,000 cfs, 0 for daily maximum flows greater than 31,500 cfs, and 1.34 – (0.00004255 × maximum daily flow), for flows between 8,000 and 31,500 cfs. This equation represents the linear decrease in flow factor from 1 at flows of 8,000 cfs to 0 for flows of 31,500 cfs.

  The computation of the *SWFF* involved taking hourly flow data and computing daily maximum flows resulting in a time series of daily maximum flows. The next step was to assign these daily maximum flows into seasonal compartments defined by *SW* for each year. *FF* values for each season were summed and normalized by the number of days in each season. The *SWFF* was then calculated as:

$$SWFF = 0.15\left(\frac{\sum_{winter} FF}{\sum Days_{winter}}\right) + 0.31\left(\frac{\sum_{spring/fall} FF}{\sum Days_{spring/fall}}\right) + 0.54\left(\frac{\sum_{summer} FF}{\sum Days_{summer}}\right)$$

SWFF is a yearly value ranging from 0 to 1, where 1 is better for camping.

The Camping Area Index (*CAI*) is a yearly value that ranges from 0 to 1, where 1 is better for camping area.

- **Visitor Experience Indices.** Visitor experience in Grand Canyon is related to navigational safety, the magnitude of within-day flow fluctuations, and the amount of time visitors can spend off river. These factors are affected by flow levels and fluctuation regimes. This relationship is based on studies documenting difficulties of motor rigs navigating rapids at lower flows, and with oar boats having their travel time and time for off-river activities affected at lower flows. The highest level of recreational impacts occurs when flows are low.

  – **Navigational Risk Index.** The Navigational Risk Index (*NRI*) was calculated in a similar fashion to the *SWFF* component of the camping area index. The *NRI* was a yearly value ranging from 0 to 1, where 1 indicates the least risk, and 0 the most.

    The seasonal weighting for *NRI* was the same as the *SW* component of the *CAI*, specifically: 0.15 for winter months (Nov., Dec., Jan., Feb.); 0.31 for spring and fall months (March, April, Sept., Oct.), and 0.54 for summer months (May, June, July, Aug.).

    The main parameter involved with the calculation of the *NRI* was the number of days where the daily minimum flow was less than 8,000 cfs.

    The computation of the *NRI* involved taking hourly flow data and computing daily minimum flow resulting in a time series of daily minimum flows. The next step was to assign these daily minimum flows into seasonal compartments defined by *SW* for each year. Then days where daily minimum flow was less than 8,000 cfs ($Days_{min}$) were identified for each season and the *NRI* was then calculated as:

$$NRI = 1 - \left\{0.15\left(\frac{\sum_{winter} Days_{min}}{\sum Days_{winter}}\right) + 0.31\left(\frac{\sum_{spring/fall} Days_{min}}{\sum Days_{spring/fall}}\right) + 0.54\left(\frac{\sum_{summer} Days_{min}}{\sum Days_{summer}}\right)\right\}$$

– **Fluctuation Index.** The Fluctuation Index (*FI*) examined the daily range in flow fluctuations relative to a defined threshold, and is a yearly value ranging from 0 to 1, where 1 indicated a desirable recreational and wilderness experience.

The daily range was the difference between the daily maximum and daily minimum flows.

Daily flow fluctuations were described as whether they are "tolerable" for recreational river use (as identified by river guides) (Table B-1) in the pertinent study by Bishop et al. (1987).

We made two assumptions in using this table of fluctuation thresholds: (1) the river flow ranges shown in the left-hand column above were determined based on the mean daily flow and (2) that the maximum fluctuation (in italics) given in the range of tolerable fluctuations in the right-hand column serves as the daily range threshold ($DR_{threshold}$) condition, above which fluctuations become increasingly more unacceptable to river users. At daily fluctuation levels greater than 10,000 cfs, fluctuations are clearly noticeable and have strong adverse effects on river users.

Fluctuations that are less than or equal to the threshold fluctuation ranges shown in the table above were assigned a value of 1 indicating an optimal condition. As daily fluctuations increased above those thresholds, the Fluctuation Index (*FI*) decreased linearly until it reached 0 when fluctuations were at or above 10,000 cfs. The equations used to calculate

TABLE B-1 Tolerable Flow Fluctuations for Recreational River Use

River Flow (cfs)	"Tolerable Fluctuation" (cfs)
5,000–8,999	2,400–*3,400*
9,000–15,999	3,900–*4,800*
16,000–31,999	6,400–*7,200*
32,000 and up	7,200–*9,800*

the fluctuation index when daily fluctuations exceeded the threshold flows shown in the table above were as follows:

- For mean daily flows between 5,000 cfs and 8,999 cfs: (–0.00015 × daily fluctuation) + 1.5151)

- For mean daily flows between 9,000 cfs and 15,999 cfs: (–0.00019 × daily fluctuation) + 1.923)

- For mean daily flows between 16,000 cfs and 31,999 cfs: (–0.00036 × daily fluctuation) + 3.5714)

- For mean daily flows at or above 32,000 cfs: (–0.005 × daily fluctuation) + 50.000)

Calculation of the *FI* involved computing mean daily flow, minimum daily flow, maximum daily flow, and daily range from the hourly flow data.

The seasonal weighting for *FI* was the same as the *SW* component of the *CAI*, specifically: 0.15 for winter months (Nov., Dec., Jan., Feb.), 0.31 for spring and fall months (March, April, Sept. Oct.), and 0.54 for summer months (May, June, July, Aug.).

The daily flow values and daily ranges were defined by seasonal use. Then for each day, mean daily flow was examined to set the value of $DR_{threshold}$ (italicized flow values in the table). The *FI* then identified days that $DR_{threshold}$ was exceeded ($Days_{exceed}$) according to:

$$FI = \left\{0.15\left(\frac{\sum_{winter} Days_{exceed}}{\sum Days_{winter}}\right) + 0.31\left(\frac{\sum_{spring/fall} Days_{exceed}}{\sum Days_{spring/fall}}\right) + 0.54\left(\frac{\sum_{summer} Days_{exceed}}{\sum Days_{summer}}\right)\right\}$$

– **Time Off River Index.** The Time Off River Index examined the amount of time visitors were able to engage in onshore activities such as hiking or visiting attractions, and was a yearly value ranging from 0 to 1, where 1 indicated the most available time off river for visitors. Calculation of the Time Off River Index involved computing mean daily flow from the hourly flow data and using this value to calculate an off river flow factor (*ORFF*).

The *ORFF* was determined as follows: 1 for mean daily flows that are greater than 31,500 cfs, 0 for flows less than 10,000 cfs, and a linear function for flows between 10,000 and 31,500 cfs ([0.0000465 × mean daily flow] – 0.465).

The seasonal weighting for *TOR* was the same as the *SW* component of the camping area index, specifically: 0.15 for winter months (Nov., Dec., Jan., Feb.), 0.31 for spring and fall months (March, April, Sept., Oct.), and 0.54 for summer months (May, June, July, Aug.).

ORFF values for each season were summed and normalized by the number of days in each season. The Time Off River Index was then calculated as:

$$0.15\left(\frac{\sum_{winter} ORFF}{\sum Days_{winter}}\right) + 0.31\left(\frac{\sum_{spring/fall} ORFF}{\sum Days_{spring/fall}}\right) + 0.54\left(\frac{\sum_{summer} ORFF}{\sum Days_{summer}}\right)$$

B.5.2 Glen Canyon Metrics

- **Glen Canyon Rafting Use Metric.** This metric represents the amount of recreational use lost in average number of visitors affected by HFEs. The metric is a single value for the 20-year analysis period (note that the range is not 0-1, but some value that is larger than 1 representing the number of lost visitor-days), where a higher value means greater adverse impact. The Glen Canyon rafting use metric uses an estimate of the average daily visitor (*ADV*) use for the months in which HFEs occur (March, April, May, Oct., Nov.). The number and duration of individual HFEs (T_{HFE}) are modeled as a part of the Sand Budget Model.

  The number of days lost for rafting because of an HFE (D_{lost}) is the duration of the HFE plus 2 days prior and 2 days post HFE ($D_{lost} = T_{HFE}$ + 2 days + 2 days) that represent the amount of time required to de-mobilize and re-mobilize rafting operations.

  The Glen Canyon rafting use metric is calculated as follows:

$$\sum_{20\ years} \left(ADV_{of\ HFE\ month}\left[\frac{visitors}{day}\right] \times D_{lost\ from\ HFE}[days]\right)$$

  The units of the Glen Canyon rafting use metric are in number of visitor-rafting days lost.

- **Glen Canyon Inundation Metric.** The Glen Canyon inundation metric represents the percentage of time that flow is above critical flow elevations that affect recreational experiences. The Glen Canyon inundation metric is a yearly value ranging from 0 to 1, where 1 indicates an optimal recreational experience.

The flow metric is calculated daily such that:

- Flow metric = 0 for daily maximum flows less than 3,000 cfs, indicating flows below 3,000 cfs are poor for boating and fishing.

- The flow metric between 3,000 cfs and 8,000 cfs was calculated using the linear function, (0.0002 × maximum daily flow) – 0.60, and flow metric values between 0 and 1. Fishing is better above 5,000 cfs, and flows for boating get progressively better up to 8,000 cfs.

- Flow metric = 1 for daily maximum flows between 8,000 and 20,000 cfs, indicating optimal conditions for boating, fishing, and shoreline access.
- The flow metric between 20,000 cfs and 31,500 cfs was calculated using the linear function, 2.739 – (0.00008695 × maximum daily flow), and flow metric values between 1 and 0. Flows above 20,000 cfs get progressively worse for boating, fishing, and shoreline access.

- Flow metric = 0 for daily maximum flows greater than 31,500 cfs. Flows above 31,500 cfs are poor for rafting, campable area, shoreline access, and fishing, and can adversely impact onshore recreational facilities.

B.6 RIPARIAN VEGETATION

Resource Goal: Maintain native vegetation and wildlife habitat, in various stages of maturity that is diverse, healthy, productive, self-sustaining, and ecologically appropriate.

Performance Metrics

- **Riparian Native States and Diversity Index.** The Riparian Native States and Diversity Index considers predicted changes over the 20-year LTEMP period in the relative cover of native vegetation community types and the relative diversity of community types. This metric was developed using a state-and-transition model developed by the Grand Canyon Monitoring and Research Center (GCMRC) (Ralston et al. 2014), which uses characteristics of annual operations to predict transitions from one vegetation type to another on different geomorphic features of the riparian zone. The model evaluates the effects of five operations (extended low flow, extended high flow, HFE, pre-dam flow, and default operation) on transitions among seven vegetation states (bare sand, common reed/cattail, horsetail/coyote willow, tamarisk, Baccharis/coyote willow, arrowweed, and mesquite). The model divides operations into growing (April–September) and non-growing seasons

(October–March) and incorporates upper and lower bar submodels, using stage elevation as a division.

Operational characteristics of each alternative were used as input to the riparian model. Output from the model was used to calculate the following component indices, which together were used to develop the overall Riparian Native States and Diversity Index:

- Relative change in cover of native vegetation community types (PM_1) (other than arrowweed) on sandbars and channel margins using the total % increase in native states predicted by an existing state and transition model for riparian vegetation communities.

$$PM_1 = \text{cover}_{\text{final}}/\text{cover}_{\text{initial}}$$

- Relative change in diversity of native vegetation community types (PM_2) (other than arrowweed) on sandbars and channel margins using the Shannon Weiner Index for richness/evenness using the results of the state and transition model.

$$PM_2 = \text{diversity}_{final}/\text{diversity}_{initial}$$

- Relative change in the ratio of native (other than arrowweed)/nonnative dominated vegetation community types (PM_3) on sandbars and channel margins using the ratio of native/nonnative communities predicted by the state and transition model.

$$PM_3 = \text{ratio}_{\text{final}}/\text{ratio}_{\text{initial}}$$

- Relative change in the arrowweed state (PM_4) on sandbars and channel margins using the total % decrease in arrowweed states predicted by the state and transition model.

$$PM_4 = \text{arrowweed}_{initial}/\text{arrowweed}_{final}$$

These individual components were combined as follows:

$$PM_n = (\Sigma w_i PM_i)$$

Where: PM_n = the performance score for Alternative n
PM_i = the score for Performance Metric i

Therefore:

$$PM_n = (PM_1 + PM_2 + PM_3 + PM_4)$$

B.7 SEDIMENT

Resource Goal: Increase and retain fine sediment volume, area, and distribution in the Glen, Marble and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes.

Performance Metrics

Two metrics were used to reflect sandbar area in Marble and Grand Canyons above 8,000 and 25,000 cfs using existing sediment modeling tools:

- **Sand Load Index.** The Sand Load Index was defined as the cumulative sand load transported by high flows (flows > 31,500 cfs) divided by cumulative sand load for entire alternative (range 0–1; higher index means a greater likelihood of larger sandbars).

- **Sand Mass Balance Index.** The Sand Mass Balance Index was defined as the mean annual sand mass balance between RM 0 and RM 61 (sand mass value, thousand metric tons; higher index means larger mass of sand in the river on average).

B.8 TRIBAL RESOURCES

A large number of resource goals have been identified in discussions with stakeholder Tribes. Although all of these goals are important to the Tribes, not all of the resources were affected by the alternatives being considered in the LTEMP DEIS. In the discussion below, resource goals that are likely to differ across LTEMP alternatives (and so matter in the selection of a preferred alternative) are listed separately from resource goals that are not likely to differ across LTEMP alternatives.

For those resource goals that are likely to distinguish LTEMP alternatives, performance metrics are identified. Performance metrics are ways that the achievement of the resource goal might be measured; these were the metrics used to evaluate the alternatives in the DEIS. For some of these resource goals, specific metrics that were amendable to quantifying differences among alternatives were not identified. Instead, the Tribes developed narrative evaluations of alternatives that were included in the DEIS. Resource goals that would be evaluated in this way in the DEIS are identified below.

1. *Increase the health of the ecosystem in Grand, Marble, and Glen Canyons*. The ecosystems in the Canyons is more than the sum of its parts, and should be healthy as a whole. Historically, in the Glen Canyon Dam Adaptive Management Program (GCDAMP), the overall health of the ecosystem has been determined by evaluating the status of each part, but this reductionist approach might possibly miss some important aspects. There are a variety of indicators of ecosystem health, including, but not limited to: the health of the

river and its ability to sustain life; the color of the water; the absence of contaminants, pollutants, and disease in the water; the potability of the water; the quality of the water that reaches Lake Mead; and the viability and health of wildlife and plants in the Canyons. It is important to understand that for many Tribes the Colorado River is a sentient being and the spiritual center of the ecosystem, as it has the capability of giving and taking life; and is prone to anger if mistreated, the health of the ecosystem depends on the health of the River.

This resource goal requires consideration of traditional ecological knowledge (TEK) and an evaluation of alternatives applying TEK was included in the narrative DEIS analysis, but not the structured decision analysis.

2. *Protect and preserve sites of cultural importance*. There are specific sites within the Canyons that are important for cultural reasons and for preservation of Tribal/religious society/kiva group/clan history (e.g., shrines, sacred sites, ancient burial sites, springs, plant collection areas, mineral collection areas, offering places, and other elements). These sites can be threatened by erosion, loss of sediment inputs, and intrusive human use (especially, non-Tribal, outside visitors). Both flow and non-flow actions (for example, education, permitting, research/monitoring, and interpretation) may affect these sites.

    a. Performance metric: *Wind Transport of Sediment Index* (see Section B.2). This index focuses on the availability of fine sediment for wind transfer to protect *National Register of Historic Places* eligible or listed sites (see Archaeological and Cultural Resources).

       It should be noted that the sites and resources that are individually *National Register of Historic Places* eligible or listed do not represent a full set of Tribal concerns. Tribal input was necessary to identify impacts to other culturally important sites or resources, and to develop an appropriate measure of their protection and preservation.

    b. Performance Metric: *Flow Effects on Historic Properties in Glen Canyon Index* (see Section B.2). In Glen Canyon, flow levels could affect resources through inundation (see Archaeological and Cultural Resources).

    c. Performance Metric: *Time Off River Index* (see Section B.2). In Grand Canyon, flow levels could increase the potential for discretionary time off the river for visitors, which could in turn result in an increased potential for archaeological sites to be visited and possibly adversely affected (see Archaeological and Cultural Resources).

    d. Performance metric: *Riparian Diversity Index*. Using results from the "Riparian Vegetation" state and transition model, this metric employed the

Shannon-Weiner Index for richness and evenness to compare relative changes in diversity of six vegetation states found on sandbars and channel margins. The equation for the Shannon-Weiner Index is:

$$-\sum_{i=1}^{n}(p_i)(\log_2 p_i)$$

where p_i is the proportion of the *i*th state of the total bar-years.
The Riparian Diversity Index was the proportion of model run diversity divided by the initial diversity found on sandbars and channel margins.

e. Performance metric: *Marsh Habitat.* Using results from the "Riparian Vegetation" state and transition model, this metric modeled change in marsh habitat. This metric compared the modeled change in marsh vegetation states (clonal wet marsh and perennial marsh) for each alternative.

f. Performance metric: *Native Fish*. Temperature suitability reflects protection and preservation of a resource important to Tribes (see Section B.1.2).

g. Assessment: *Access to Springs.* For most Tribes, all springs and seeps are sacred. Access to culturally important springs may be affected by flow levels. Springs were evaluated in the DEIS to determine if alternatives differ in terms of the ability of Tribes to access them under varying flow conditions.

3. *Preserve and enhance respect for life*. The Tribes see life itself as sacred and believe that human activities should protect and promote life, not destroy life. There are two aspects to this objective: first, minimize the taking of life; and second, encourage the expansion and proliferation of life forms. These are both complex concepts. The Tribes recognize that it is appropriate for humans to take other life in some circumstances, especially when it promotes other life (particularly our own consumption for survival), but this taking needs to be minimal and respectful because there are spiritual consequences associated with the taking of life. The promotion of life does not necessarily imply a return to historical or "natural" conditions—the Glen Canyon Dam has encouraged new life in Glen, Marble, and Grand Canyons, so a return to pre-Dam conditions is not necessarily implied by this objective, nor is there a strong distinction between native and nonnative species among all Tribes.

   a. Performance metric: *The average number of years in which trout mechanical removal trips occur.* As a coarse measure of the impact of killing trout, this allows a distinction between alternatives that minimize mechanical removal. But the nature of the take, the purpose behind it, the methods of take, the disposition of the trout taken, and the mindset of those killing the fish also affect the sacred treatment of living beings. This performance metric was calculated from the coupled trout-humpback chub models.

b. Performance metric: *The average number of years in which trout management flows occur*. Trout management flows, designed to reduce reproduction or survival of juvenile trout, are considered to be killing by some Tribes, and should be minimized. Alternatives that include trout management flows are likely to differ in how often the flows are triggered, so this performance metric might ultimately help to distinguish the alternatives. This performance metric was calculated from the coupled trout-humpback chub models.

4. *Preserve and enhance the sacred integrity of Grand, Marble, and Glen Canyons*. Grand, Marble, and Glen Canyons are sacred to many Tribes, and the preservation of their sacred integrity is important. The sanctity of the Canyons may be threatened by human impacts and behaviors, development, and the presence of artificial structures and activities. An important aspect of the sanctity is the intentionality of visitors: when outsiders enter the Canyons (on boat or hiking trips), the respect they show to the Canyons and Colorado River can affect the spiritual integrity. There are many consequences of the disturbance of this sanctity, including but not limited to: a reduction of the spiritual strength of plants gathered and used by the Navajo for medicinal and cultural purposes; an inability to retire Navajo sacred objects into the Colorado River, when they have become too old for continued use; weakening of the sacred role the Canyons play as a final resting place for Hopi; and an overall disruption of the state of mind and spirit of Zuni religious leaders and their experience of being within a very sacred place that embodies the Zuni emergence, migrations, creation of medicine bundles, and the communion with the spirits of Zuni ancestors.

a. Assessment: This resource goal, while of profound importance to the Tribes, is not thought to differ measurably across the alternatives under consideration in the LTEMP DEIS, because it is not driven by flow operations from the dam or currently envisioned attendant activities. Future science plans could include activities that are objectionable to the Tribes. Future science planning should include meaningful consultation with the Tribes. This goal was evaluated in the narrative DEIS analysis, but not the structured decision analysis.

5. *Maintain and enhance healthy stewardship opportunities*. Several of the Tribes have been given a sacred stewardship responsibility for the preservation and harmony of the world. For example, the Hopi have a covenant with *Ma'saw* to be stewards of the earth; other Tribes have similar stewardship ethics grounded in spiritual traditions. To maintain these

stewardship responsibilities, the Tribes need to be an active part of stewardship of the Canyons. This stewardship includes: ceremonial activities, whether performed in the Canyons or in the villages; participation in management of the Canyons, including water management, both through traditional practices and Western management activities; and education, to maintain cultural knowledge and connection with the Canyons. The Tribes note that the Federal Government also has stewardship responsibilities that arise out of federal legislation; because this federal involvement has sometimes taken stewardship responsibility from the Tribes, it is critical that the Federal Government be accountable for its stewardship. At times, the colonial presence of the Federal Government has made it more difficult for Tribes to carry out their stewardship responsibilities; the Tribes need the autonomy to undertake their responsibilities. Successful development of joint stewardship among the Tribes and Federal Government will require continued building of mutual respect and trust between those entities.

   a. Assessment: Tribal stewardship opportunities are not tied to individual alternatives being considered in the LTEMP DEIS, but could be crafted to apply to any of the alternatives. Thus, this resource goal, while of critical importance to the Tribes individually, as well as to the ongoing relationship between the Tribes and the Federal Government, may not help distinguish among the alternatives. This goal was evaluated in the narrative DEIS analysis, but not the structured decision analysis.

6. *Maintain and enhance the Tribal connections to the Canyons*. The spiritual, historical and cultural connections that Tribes have to the Canyons require the protection of sacred sites and the integrity of the Canyons as a whole, but protection alone is not enough. The Tribes also need opportunities for access, education, and stewardship to keep their connections vibrant. Access can be undermined by physical barriers, by the requirement of permits from a colonial authority, and by the effects of human activity that decrease the power of those sites and the experience when at them (e.g., lack of privacy, disturbance of the soundscape and viewshed).

   a. Assessment: Like the sacred integrity and stewardship resource goals, this resource goal is not thought to differ across the alternatives. The flow operations of Glen Canyon Dam are not likely to affect Tribal access, education, spiritual ceremonies, or other connections to the Canyons. This resource goal may be more appropriately addressed through government-to-government consultation in other forums. This goal was evaluated in the DEIS, but not the structured decision analysis.

7. *Increase economic opportunity*. The Canyons, the Colorado River, and the dam are sources of economic benefit for the Tribes in the area. The Canyons provides tourism and other opportunities that enhance the economic well-being of Tribes. (As an important note, tourism can also undermine the well-

being of Tribes in aspects other than economic; see the other Tribal resource goals.) Glen Canyon Dam provides affordable electricity for Tribal needs, as well as for development projects.

a. Assessment: *projected annual economic benefit for the Hualapai Tribe associated with river-running tourism.* During discussions with Tribal representatives, one particular economic concern was raised by Hualapai river runners, namely, the effect on tourism operations of extensive sediment deposition downstream of Diamond Creek. There is a narrative analysis of the effect of dam operations on Hualapai River running in the DEIS.

b. Assessment: Note that the economic benefit directly associated with hydroelectric power is measured through the hydroelectric performance metrics. A recreation economics model was used to determine the value of recreational use of Lake Powell, Lake Mead, and the Colorado River downstream of Glen Canyon Dam.

8. *Maintain Tribal water rights and supply*. Tribes in the area depend on the Colorado River for many of their water needs, so the preservation of established, traditional, and desired water rights, both now and into the future, is important. There are a number of claims to water rights that have been asserted by the Tribes, but for which there are not yet quantified rights through decree or negotiated settlement; these water rights are as important as the established water rights.

   a. Sidebar for LTEMP DEIS alternatives: based on its purpose and need, the LTEMP DEIS is not intended to include any alternatives that violate agreed-upon Tribal water rights.

   b. Performance metric: *Lake Powell water elevation.* This metric evaluates the frequency with which Lake Powell elevations drop below critical levels where existing or proposed intakes are.

9. *Process objectives*. There are several important process objectives—objectives that govern *how* the LTEMP decision is made, rather than what decision is made. The first of these is the genuine incorporation of Tribal input to the LTEMP process, as a reflection of Federal trust responsibilities. The second is the importance of incorporating learning, to improve management over time; in this spirit, an experimental approach that can result in adaptive management is favored.

   a. Assessment: (a) It is the intention of the Department of the Interior and the joint-lead Federal agencies to genuinely incorporate Tribal input into the LTEMP process, and this has been undertaken through face-to-face meetings with individual Tribes who have requested such meetings, as well as regular conference calls with Tribal representatives. The Tribes are included in all Cooperating Agency and stakeholder meetings. Continued involvement of Tribes in the LTEMP process will occur. (b) The evaluation of experimental alternatives and the development of a long-term monitoring program associated with the LTEMP DEIS will occur in a later stage of analysis. The purpose and need for the DEIS includes the appropriate incorporation of learning. Thus, this resource goal is an important part of how the process was designed for LTEMP, but it does not help distinguish among the alternatives (because the alternatives do not differ in this regard).

B.9 WATER DELIVERY

Resource Goal: Ensure that water delivery continues in a manner that is fully consistent with and subject to the Colorado River Compact, the Upper Colorado River Basin Compact, the Water Treaty of 1944 with Mexico, the decree of the Supreme Court in *Arizona v. California*, and the provisions of the Colorado River Storage Project Act of 1956 and the Colorado River Basin Project Act of 1968 that govern allocation, appropriation, development, and exportation of the waters of the Colorado River Basin.

Calculated Metrics (not used in the structured decision analysis process)

- Frequency of deviation from the Alternative A (No Action Alternative) to Lake Powell Annual Operating Tier as specified by the 2007 Interim Guidelines (Reclamation 2007). The Operating Tier was predicted using the CRSS RiverWare model.

- Probability over time of Lake Powell being in each Operating Tier as specified in the 2007 Interim Guidelines (Reclamation 2007). The Operating Tier was predicted using the CRSS RiverWare model.

- Frequency and volume of exceptions to meeting the annual release target volumes specified by the 2007 Interim Guidelines (Reclamation 2007). The target and actual annual release volumes were predicted using the CRSS RiverWare model.

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APPENDIX C:

DECISION ANALYSIS TO SUPPORT DEVELOPMENT OF THE GLEN CANYON DAM LONG-TERM EXPERIMENTAL AND MANAGEMENT PLAN

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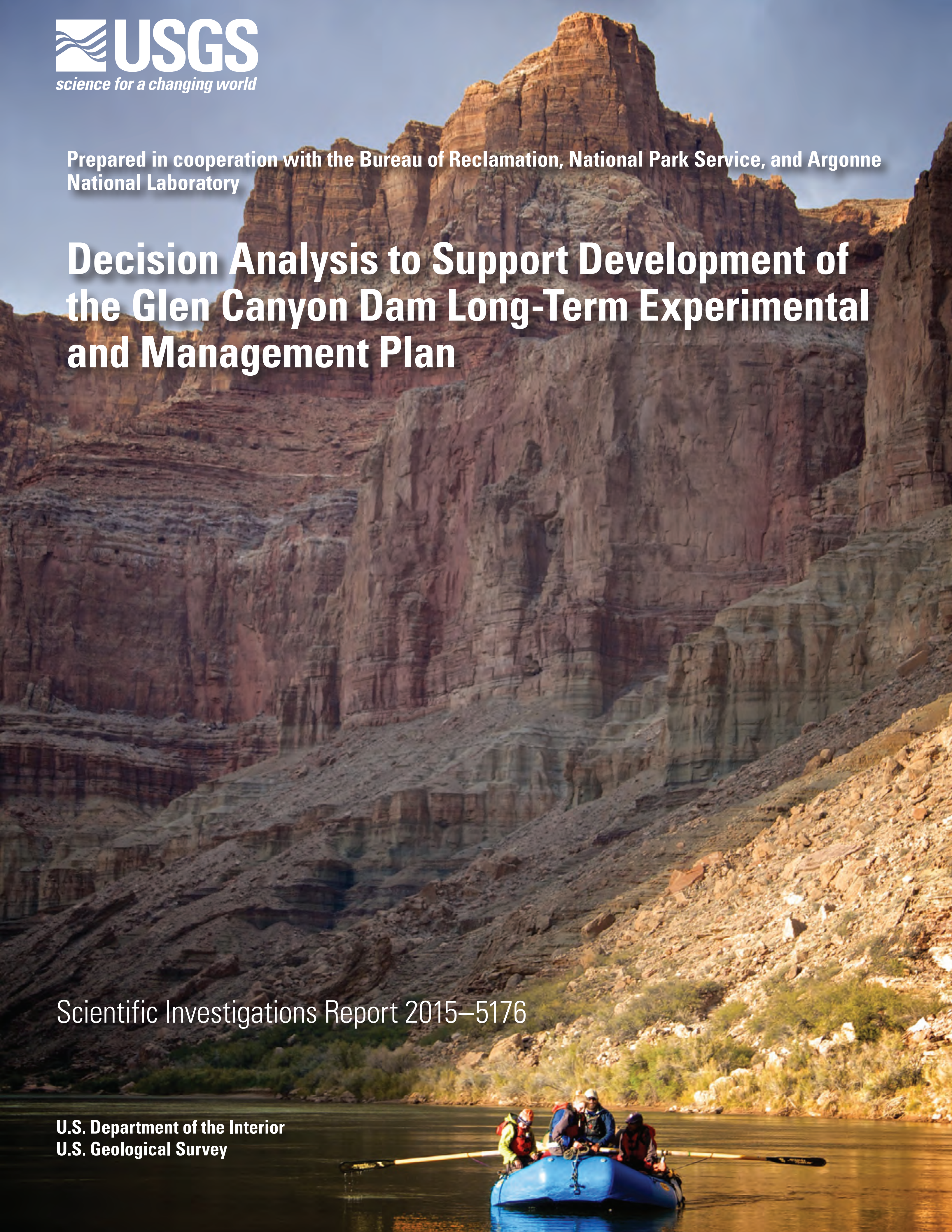

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Decision Analysis to Support Development of the Glen Canyon Dam Long-Term Experimental and Management Plan

Scientific Investigations Report 2015–5176

U.S. Department of the Interior
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Covers. Front: An oar boat with university students from Northern Arizona University's Grand Canyon Semester passes river mile 61 near the confluence of the Little Colorado River and the Colorado River. This area is known for its biological and cultural significance, as the stronghold of the endangered humpback chub, and a place of importance in many tribal histories. Photograph taken by Amy S. Martin, Northern Arizona University, November 2014.

Back: Lower Beaver Falls lies approximately 4 miles up Havasu Creek from its confluence with the Colorado River at river mile 157 and is the site of ongoing endangered humpback chub translocations. Photograph taken by Amy S. Martin, National Park Service, October 2013.

Decision Analysis to Support Development of the Glen Canyon Dam Long-Term Experimental and Management Plan

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Conversion Factors

[Inch/Pound to International System of Units]

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acrea-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

ADWR	Arizona Department of Water Resources
AGFD	Arizona Game and Fish Department
AMWG	Adaptive Management Working Group
Argonne	Argonne National Laboratory
Aurora	AURORAxmp
AZGFD	Arizona Game and Fish Department
BIA	Bureau of Indian Affairs
CMIP3	Coupled Model Intercomparison Project Phase 3
CREDA	Colorado River Energy Distributors Association
CRSP	Colorado River Storage Project
CRSS	Colorado River Simulation System
DEIS	Draft Environmental Impact Statement
DFC	desired future condition
DOI	U.S. Department of the Interior
DT	Decision-Theoretic school of adaptive management
EIS	Environmental Impact Statement
ESA	Endangered Species Act of 1973
EVPI	expected value of perfect information
EVXI	expected value of partial information
FWS	U.S. Fish and Wildlife Service
GCDAMP	Glen Canyon Dam Adaptive Management Program
GCMRC	Grand Canyon Monitoring and Research Center
GCPA	Grand Canyon Protection Act of 1992
GCRG	Grand Canyon River Guides
GTMax-Lite	Generation and Transmission Maximization model, spreadsheet version
HBC	humpback chub (*Gila cypha*)
HFE	high-flow experiment
IFFF	International Federation of Fly Fishers
LTEMP	Long-Term Experimental and Management Plan
MCDA	multicriteria decision analysis
MLFF	Modified Low Fluctuating Flow
NEPA	National Environmental Policy Act
NPCA	National Parks Conservation Association
NPS	National Park Service

NPV	net present value
O&M	operating and maintenance
RBT	rainbow trout (*Onchorhynchus mykiss*)
RE	Resilience-Experimentalist school of adaptive management
Reclamation	Bureau of Reclamation
RM	river mile
ROD	Record of Decision
SDA	structured decision analysis
SDM	structured decision making
SLI	sand load index
SMART	Simple Multi-attribute Rating Technique
SME	subject-matter expert
SRP	Salt River Project
TMF	trout management flow
UAMPS	Utah Associated Municipal Power Systems
WAPA	Western Area Power Administration
WTSI	wind transport of sediment index

Decision Analysis to Support Development of the Glen Canyon Dam Long-Term Experimental and Management Plan

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1 Abstract

The U.S. Geological Survey, in cooperation with the Bureau of Reclamation, National Park Service, and Argonne National Laboratory, completed a decision analysis to use in the evaluation of alternatives in the Environmental Impact Statement concerning the long-term management of water releases from Glen Canyon Dam and associated management activities. Two primary decision analysis methods, multicriteria decision analysis and the expected value of information, were used to evaluate the alternative strategies against the resource goals and to evaluate the influence of uncertainty.

A total of 18 performance metrics associated with 8 out of 12 resource goals (fundamental objectives) were developed by the Bureau of Reclamation and National Park Service in partnership with subject-matter teams composed of Federal, State, tribal, and private experts. A total of 19 long-term strategies associated with 7 alternatives were developed by the Bureau of Reclamation, National Park Service, Argonne National Laboratory, U.S. Geological Survey, and Cooperating Agencies. The 19 long-term strategies were evaluated against the 18 performance metrics using a series of coupled simulation models, taking into account the effects of several important sources of uncertainty. A total of 27 Federal, State, tribal, and nongovernmental agencies were invited by the Assistant Secretary of Interior to participate in a swing-weighting exercise to understand the range of perspectives about how to place relative value on the resource goals and performance metrics; 14 of the 27 chose to participate. The results of the swing-weighting exercise were combined with the evaluation of the alternatives to complete a multicriteria decision analysis. The effects of uncertainty on the ranking of long-term strategies were evaluated through calculation of the value of information.

The alternatives and their long-term strategies differed across performance metrics, producing unavoidable tradeoffs; thus, there was no long-term strategy that was dominated by another across all performance metrics. When the performance of each alternative was weighted across performance metrics, three alternatives (B, D, and G) were top-ranked depending on the set of weights proposed: Alternative B was favored by those stakeholders that placed a high value on hydropower; Alternative G was favored by those stakeholders that placed a high value on the restoration of natural processes, like beach-building and natural vegetation; and Alternative D was favored by the remaining stakeholders. Surprisingly, these rankings were not sensitive to the critical uncertainties that were evaluated; that is, the choice of a preferred long-term strategy was sensitive to the value-based judgment about how to place relative weight on the resource goals but was not sensitive to the uncertainties in the system dynamics that were evaluated in this analysis. The one area of uncertainty that did slightly affect the ranking of alternatives was the long-term pattern of hydrological input; because of this sensitivity, some attention to the possible effects of climate change is warranted.

The results of the decision analysis are meant to serve as only one of many sources of information that can be used to evaluate the alternatives proposed in the Environmental Impact Statement. These results only focus on those resource goals for which quantitative performance metrics could be formulated and evaluated; there are other important aspects of the resource goals that also need to be considered. Not all the stakeholders who were invited to participate in the decision

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analysis chose to do so; thus, the Bureau of Reclamation, National Park Service, and U.S. Department of Interior may want to consider other input.

2 Introduction

The Glen Canyon Dam is on the Colorado River in Arizona, United States, within the boundaries of Glen Canyon National Recreation Area and upstream from Grand Canyon National Park (fig. 1) and is managed by the Bureau of Reclamation (hereinafter referred to as "Reclamation"). The Glen Canyon Dam Adaptive Management Program (GCDAMP) was established in 1997 to provide research and monitoring of downstream resources to Reclamation and the U.S. Department of the Interior (DOI). The GCDAMP project area stretches along the Colorado River from the forebay of Glen Canyon Dam to the westernmost boundary of Grand Canyon National Park. Locations along the Colorado River are indexed by river miles (RM) with a reference point at Lees Ferry (RM 0). The Glen Canyon Dam is at RM -15.5 (15.5 mi upstream from Lees Ferry). Other important locations that are referenced in this report include the following: Paria River (RM 1.0), Little Colorado River (RM 61.4), and Bright Angel Creek (RM 87.8) (fig. 1). The reach from Glen Canyon Dam to Lees Ferry is known as Glen Canyon, the reach from Lees Ferry to the Little Colorado River is known as Marble Canyon, and Grand Canyon proper begins at the Little Colorado River.

In October 1996, the Secretary of the Interior signed a Record of Decision (ROD) documenting the selection of operating criteria for Glen Canyon Dam (Bureau of Reclamation, 1996) as analyzed in the 1995 Final Environmental Impact Statement (Bureau of Reclamation, 1995). The preferred alternative, known as Modified Low Fluctuating Flow (MLFF), has governed the operation of Glen Canyon Dam for the last 19 years (1996 to present) with important modifications described in "Final Environmental Impact Statement—Colorado River interim guidelines for lower basin shortages and the coordinated operations for Lake Powell and Lake Mead" (Bureau of Reclamation, 2007), "Environmental Assessment—Development and implementation of a protocol for high-flow experimental releases from Glen Canyon Dam" (Bureau of Reclamation, 2011a), "Environmental Assessment—Non-native fish control downstream from Glen Canyon Dam" (Bureau of Reclamation, 2011b), and many other regulatory documents. The Bureau of Reclamation (1996) also established the GCDAMP and Grand Canyon Monitoring and Research Center (GCMRC), which has led extensive monitoring and research aimed to improve the management of the Colorado River and its environs below Glen Canyon Dam.

In July 2011, the Secretary of the Interior announced the intent to develop a Long-Term Experimental and Management Plan (LTEMP) and Environmental Impact Statement (EIS) for Glen Canyon Dam as the first comprehensive review of dam operations in 15 years and as an opportunity to integrate the considerable scientific information collected since the GCDAMP began in 1996. The Bureau of Reclamation and National Park Service (NPS) are serving as joint-lead agencies for the EIS. The following agencies are participating as Cooperating Agencies in development of the EIS: Arizona Game and Fish Department (AGFD), Bureau of Indian Affairs (BIA), Colorado River Board of California, Colorado River Commission of Nevada, the Havasupai Tribe, the Hopi Tribe, the Hualapai Tribe, the Kaibab Band of Paiute Indians, the Navajo Nation, the Pueblo of Zuni, Salt River Project (SRP), U.S. Fish and Wildlife Service (FWS), Upper Colorado River Commission, Utah Associated Municipal Power Systems (UAMPS), and Western Area Power Administration (WAPA).

The purpose of the LTEMP is to provide a comprehensive framework for adaptively managing Glen Canyon Dam over the next 20 years consistent with the Grand Canyon Protection Act of 1992 (GCPA) and other provisions of federal law (Bureau of Reclamation and National Park Service 2015); thus, the preferred alternative ultimately selected for the LTEMP will govern the management of water releases at Glen Canyon Dam for the next 20 years, specifying condition-dependent seasonal, weekly, and daily patterns of release, as well as nonflow actions, including vegetation management and the potential for mechanical removal of nonnative fish. The goals for the LTEMP are to meet the requirements of the GCPA; and to minimize, consistent with the law, adverse effects on the downstream natural, recreational, and cultural resources in Glen Canyon National Recreation Area and Grand Canyon National Park, including resources of importance to American Indian Tribes, while ensuring water delivery and maintaining or increasing hydroelectric capacity and generation. The need for the LTEMP arises from scientific information developed since the 1996 record of decision (Bureau of Reclamation, 1996), the use of which will better inform DOI decisions on dam operations and other management and experimental actions so that the Secretary of the Interior may continue to meet statutory obligations to protect resources downstream from Glen Canyon Dam for future generations, conserve species listed under the Endangered Species Act of 1973 (ESA), avoid or mitigate effects on National Register eligible properties, and protect tribal interests, while meeting water delivery obligations and providing hydropower generation. The list of resources of concern in the analysis of alternatives includes the following: tribal resources and interests, sediment deposition and retention, riparian vegetation, humpback chub (HBC) (*Gila cypha*) and other native fish, historic properties, recreation, the rainbow trout fishery in Glen Canyon, water delivery, and hydropower. There is uncertainty about how management actions in this system affect the resources of concern, which complicates the analysis of alternatives. There is an acknowledged need for adaptive management (Walters, 1986), perhaps even for experimental actions chosen to accelerate learning for the benefit of selecting future management actions. The decision problem, therefore, can be characterized as one of multiple objective tradeoffs in the face

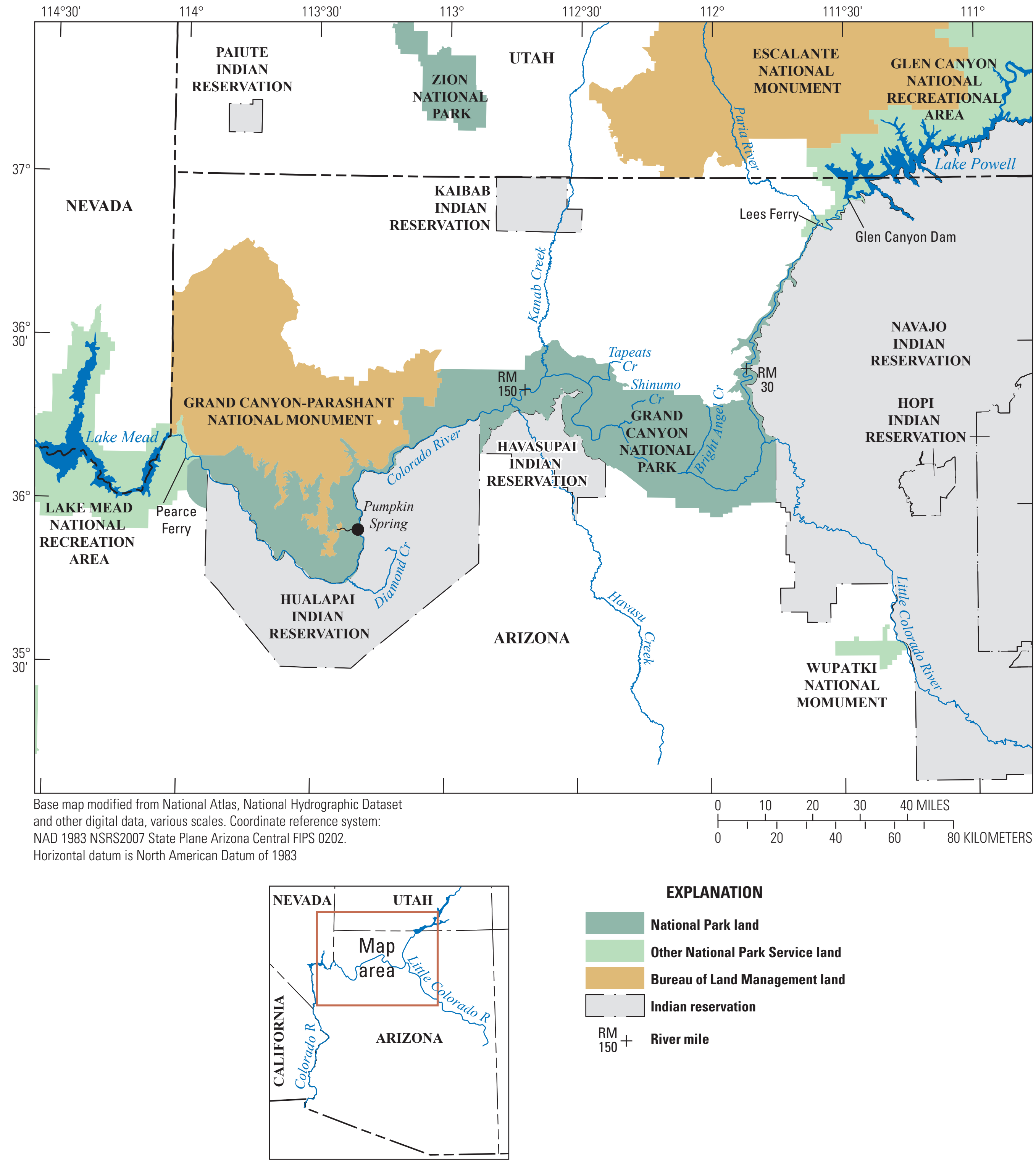

Figure 1. The Colorado River ecosystem below Glen Canyon Dam, depicting the Glen Canyon Dam Adaptive Management Program project area.

of uncertainty, where the management actions themselves are condition-dependent, information-dependent, and complex; and where there is the opportunity to reduce uncertainty early on to improve later actions through adaptive implementation.

In July 2012, the Assistant Secretary of the Interior for Water and Science, Reclamation, and NPS embraced the idea of using structured and formal decision analysis as one of several tools to evaluate alternatives in this EIS. Formal decision analysis was seen as a way to address multiple objectives, engage stakeholders, and evaluate the degree to which uncertainty is an impediment to the selection of management actions.

The purpose of this report is to document the formal decision analysis completed by the U.S. Geological Survey, in cooperation with the Bureau of Reclamation, National Park Service, and Argonne National Laboratory, as one component of the evaluation of alternatives for the LTEMP EIS. This report is a stand-alone document and an appendix to the Draft EIS (Bureau of Reclamation and National Park Service, 2015); it is also anticipated to be an appendix to the Final EIS. The emphasis in this report is on the decision analysis; the reader is referred to the Draft EIS (DEIS) and its appendixes for many other details, including the following: the legal, ecological, and cultural context of the LTEMP; an indepth description of the alternatives; the details of the quantitative models used to evaluate the alternatives; and a comprehensive comparison of the alternatives and their effects on resources of concern, including qualitative assessments that were not included in the decision analysis.

3 Decision Analysis

The DOI is including formal decision analysis tools to accompany more traditional qualitative tools to evaluate alternatives in the Glen Canyon Dam LTEMP EIS. The LTEMP EIS concerns the management of a very complex system with many, possibly competing, resources of interest and considerable uncertainty about the relations between management strategies and the responses of resources of interest to management strategies; furthermore, there are multiple stakeholder viewpoints to consider, and the DOI wants to use a structured process as one of the tools for better evaluating and understanding stakeholder viewpoints. This section provides an overview of decision analysis and describes the quantitative methods the DOI used to analyze the alternatives.

3.1 Structured Decision Making

"Structured decision making" (SDM) is a term of art, used by a community of practitioners in the United States, Canada, and Australia, to refer to the application of a broad array of decision analysis tools to natural resource management (Gregory and others, 2012). The analytical tools used in any application will depend on the specific needs of that decision setting, so SDM can look quite different from case to case. The set of analytical tools that might be used include the following: multicriteria decision analysis (MCDA), decision trees, expert elicitation, objectives hierarchies, value of information, stakeholder involvement, predictive modeling, utility theory, dynamic optimization, portfolio analysis, and many others. The common features in any application of decision analysis are (1) an attention to value-focused thinking (Keeney, 1996), recognizing that any decision is an attempt to achieve something of value to the decision maker; and (2) decomposing the decision problem into basic elements (objectives, alternatives, consequences, and tradeoffs) (Runge, 2011). The goal of SDM is to provide a transparent process for articulating objectives, developing alternatives, and evaluating those alternatives against the objectives. Note, however, that SDM does not substitute for a decision maker, and the application of the SDM process does not make a decision; rather, SDM only serves to aid the decision maker in understanding and organizing the complexities of the problem. The DOI prefers to use the term "structured decision analysis" or simply "decision analysis" for the LTEMP EIS process because the Secretary of the Interior retains the responsibility and authority to make a decision. In the context of the LTEMP EIS, two key decision analysis tools are used to evaluate the alternatives: MCDA and the expected value of perfect information (EVPI).

3.2 Multicriteria Decision Analysis

Many objectives associated with management of Glen Canyon Dam are important to stakeholders, including tribal cultural and spiritual values, endangered species, hydropower generation, sediment conservation, and recreation. It is possible that some of these objectives compete; if so, no single strategy will be best at achieving all the objectives. One of the difficulties the decision maker faces, then, is the value judgment regarding how to weight this host of objectives based on the many statutes governing Glen Canyon Dam operation and resource protection. Multicriteria decision analysis is a formal decision analysis tool designed to help evaluate the competing objectives and explore how to weight them within the context of the statutes (Figueira and others, 2005), and has been applied to a wide variety of natural resource management problems (Herath and Prato, 2006). Considerable literature advocates the use of MCDA in National Environmental Policy Act (NEPA) processes (Gregory and others, 1992; Kulkarni and others, 1993; Prato, 1999; Sheehy and Vik, 2002; Kiker and others, 2005; Linkov and others, 2006a, 2006b, 2006c; Stich and Holland, 2011; Marcot and others, 2012). Although not common, a few examples of NEPA documents explicitly incorporate MCDA methods (National Oceanic and Atmospheric Administration, 1995a, 1995b; Kimbrough and others, 2008; Nobrega and others, 2009; Bureau of Reclamation, 2011b; Runge and others, 2011a). Notably, the value of using MCDA for evaluation of management alternatives for Glen Canyon Dam has been argued by Flug and others (2000).

One of the key advantages of MCDA in the context of the LTEMP EIS is that it provides a structured and transparent method for receiving detailed stakeholder input about the resource goals, ways to evaluate performance of the alternatives against the resource goals, and the value of resource goals relative to each other. Stakeholders have legitimate differences in viewpoint about the relative importance of the objectives affected by the LTEMP alternatives, differences that stem from policy judgments rather than scientific judgments. Multicriteria decision analysis provides a way for stakeholders to articulate those judgments. By clearly understanding those different viewpoints, Reclamation and NPS (hereinafter referred to as the "joint-lead agencies") were better able to analyze and compare the alternatives and ultimately advise the Secretary of the Interior regarding her choice of a preferred alternative. In selecting a preferred alternative, the Secretary of the Interior needed to consider the appropriate suite of laws, regulations, agency guidance, and policies; the language in the purpose and need statement; stakeholder input; and the public input at various points in the process. The MCDA helped organize at least part of that complex input.

3.2.1 A Full Articulation of Resource Goals

The first step in a MCDA is a full articulation of the resource goals important to the decision maker, stakeholders, and the public. The set of resource goals should be (1) complete because it should cover the full range of concerns relevant to the decision; (2) concise because it should not contain redundant or irrelevant resource goals; (3) sensitive so that the resource goals are able to distinguish the performance of the alternatives under consideration; (4) understandable so that the resource goals directly communicate what matters; and, if possible, (5) independent so that the resource goals describe unique aspects of the problem (Gregory and others, 2012). The completeness of the set of resource goals is often very important because it provides objectivity and transparency to otherwise invisible values (Turner and others, 2008).

In an MCDA, the focus of the resource goals should be should be on objectives that are fundamental (called "fundamental objectives") to the decision maker, stakeholders, and public. Fundamental objectives, as distinguished from means objectives, are objectives that are important in their own right—they are the desired outcomes of the decision, not because they lead to something else of importance but because of their inherent value. Means objectives are pursued as a pathway to fundamental objectives but are not themselves of inherent value to the decision maker; for example, a high juvenile survival rate of HBC is important as a means to achieving a sustainable population of HBC in the Colorado River below Glen Canyon Dam, but juvenile survival is not itself the objective that the decision maker fundamentally cares about. Achieving population sustainability with low or moderate juvenile survival rates of HBC, if possible, would be acceptable; thus, the fundamental objective concerns population sustainability.

The joint-lead agencies, in consultation with the tribes and Cooperating Agencies and with input from public scoping comments, developed a set of resource goals, which represent the fundamental objectives to be pursued in the LTEMP EIS. Some of these resource goals are closely aligned with the desired future conditions (DFCs) developed by the Adaptive Management Working Group (AMWG); and are grounded in the laws, regulations, and policies relevant to the joint-lead agencies. In a few instances, the resource goals differ from the DFCs to more clearly identify a set of fundamental objectives for the specific context of the LTEMP EIS that meet the characteristics described previously in this section (complete, concise, sensitive, understandable, and independent). In a parallel effort, the joint-lead agencies worked directly with interested tribes to develop resource goals that are specific to tribal perspectives.

3.2.2 Performance Metrics

Performance metrics are scales of measurement on which the fundamental objectives (resource goals) can be evaluated. By developing performance metrics that are closely tied to the resource goals, the assessment of alternatives can include a quantitative, rather than solely narrative, analysis. Also, articulation of performance metrics forces considerable clarity about the resource goals; thus, using performance metrics encourages a high degree of transparency in the analysis of alternatives. It is difficult, however, to express all the resource goals in quantitative form. The use of performance metrics, therefore, does not preclude use of narrative analyses to evaluate additional resource goals in a NEPA process.

Ideally, performance metrics should directly reflect the resource goals, but this is often very difficult to achieve because the resource goals can be subtle, nuanced, complex, and difficult to quantify. There are also cases where a desired performance metric can be articulated, but the scientific tools do not exist to predict the performance of alternatives on that scale; thus, development of performance metrics is a very important science-policy interface. For the management agency, the desire is to have performance metrics that closely track the corresponding resource goals, but for the scientists, the desire is to have performance metrics that can be predicted with high confidence. When the difference between these desires is large, the question is how far the quantitative assessment can stretch toward the desired performance metric while maintaining a robust scientific foundation. There is, of course, a tendency to want to use proxy metrics that can be reliably predicted (for example, temperature as a proxy for HBC recruitment), but this only shifts a difficult burden to the decision maker who has to then make invisible judgments about how closely the proxy aligns with the underlying resource goal. The performance metrics developed for this decision analysis span the gamut from direct, natural measures of resource goals to distant proxies, depending on the science available to support their assessment. An effort has been made to transparently articulate the relation between each performance metric used and the resource goal it represents.

The joint-lead agencies in conjunction with subject-matter expert (SME) teams from all relevant disciplines developed performance metrics corresponding to the resource goals that were used as the scales on which alternatives were quantitatively evaluated. During the course of development, the joint-lead agencies sought feedback on draft performance metrics from the Cooperating Agencies, tribes, and other stakeholders.

3.2.3 Transparent and Quantitative Evaluation of Alternatives

As part of the effects analysis for the LTEMP EIS, and as a supplement to the traditional narrative analysis, Argonne National Laboratory (hereinafter referred to as “Argonne”) and collaborators completed quantitative analyses of the alternatives against the performance metrics. These quantitative analyses are an exercise in forecasting—predicting the relative performance of the alternatives against the resource goals using the best available science. In some cases, existing models were available for this task; in other cases, new predictive models were developed; and in still other cases, formal methods of expert elicitation (Martin and others, 2012) were needed. But, in all cases, the methods for assessing the alternatives provide transparency to the evaluation.

The ecological, economic, and social systems being evaluated in the LTEMP EIS are complex, and even though the systems are some of the best studied systems in the world, they are nevertheless incompletely understood; thus, the models used to predict performance of the alternatives were necessarily simplifications of the real world and had to account for uncertainty. Specific details about how uncertainty was handled in the decision analysis are described in section 3.3, “Uncertainty, Value of Information, and Adaptive Management.”

A traditional, narrative evaluation of alternatives has to make all the same assumptions as a quantitative evaluation does. The use of a quantitative approach raises the degree of transparency about these assumptions and allows better inspection by interested parties. Also, quantitative analysis of the alternatives provides the raw material for later steps in a decision analysis.

3.2.4 Tradeoff Analysis

The outcome of the assessment phase can be viewed as a “consequence table”—a summary of how each alternative is expected to perform against each resource goal (as expressed by the corresponding performance metric). That assessment phase is a scientific endeavor—an evaluation of the current knowledge of the system to forecast how the system will respond to any proposed alternative. The consequence table provides a visual way to compare the alternatives and is an important analytical and communication step. Selection of a preferred alternative involves a policy choice based on sound science, which requires a values judgment about how to comply with the laws applicable to the proposed action while achieving a multitude of fundamental objectives, particularly if there are tradeoffs among the objectives. Some fundamental objectives, because of legal and policy considerations, may take precedence over other objectives; the remaining objectives need to be balanced appropriately. The joint-lead agencies, in evaluating the alternatives and providing a recommendation to the Secretary of the Interior, wanted to understand how Cooperating Agencies and other stakeholders would individually value the range of resource goals. This structured input was not the only consideration; in the NEPA process, decisions are also informed by the legal and policy framework, including relevant laws, regulations, agency policies and guidance, court cases, consultation with tribes, and public comment at various points in the process.

Multicriteria decision analysis provides tools for eliciting and investigating the values judgments associated with balancing tradeoffs. There are a variety of MCDA methods; we used the Simple Multi-Attribute Rating Technique (SMART) (Edwards, 1971; Goodwin and Wright, 2004) with swing weighting (Winterfeldt and Edwards, 1986). Stakeholders were asked to individually complete a swing-weighting exercise to express how they valued the resource goals relative to one another, while accounting for the range in performance across alternatives. The weights derived were combined with the consequence table to rank the alternatives from the viewpoint of each participating stakeholder. These individual viewpoints were provided as input to the joint-lead agencies and are documented in this report.

3.3 Uncertainty, Value of Information, and Adaptive Management

The second major set of tools from decision analysis that were used in the development and assessment of alternatives for the LTEMP EIS concern how to articulate, evaluate, and address uncertainty in an adaptive design. The primary analytical tool that informed this process is the expected value of information (Raiffa and Schlaifer, 1961; Howard, 1966). In a decision analysis context, the value of information is the best method for sensitivity analysis (Felli and Hazen, 1998). Runge and others (2011b) describe how the value of information can be used to design an adaptive management program that focuses on finding the best management strategy (rather than reducing the most uncertainty).

3.3.1 Adaptive Management Versus Experimental Management

Several different schools of adaptive management, which differ in their emphasis on various decision analysis tools and approach to experimental design, exist (McFadden and others, 2011). All the schools trace their lineage back to Walters

(1986), but their current approaches can look very different. In the Resilience-Experimentalist (RE) school of adaptive management, emphasis is placed on experimental design focused on policy choices (management alternatives) as the elements of uncertainty. To some extent, the RE school is most focused on "unknown unknowns"—uncertainty that cannot be anticipated in advance—and, therefore, advocates robust experimental designs composed of management alternatives to provide accelerated learning about the system dynamics in response to management. This accelerated learning might not be formally linked to subsequent long-term management planning because of a sense that there is too much hubris in making long-term plans when so much surprise is expected. The RE school perhaps draws more inspiration from Walters and Holling (1990) than from the seminal text (Walters, 1986). Examples of adaptive management that are often associated with the RE school include management in the Columbia River Basin, water management in the Everglades, and past management in the GCDAMP (McFadden and others, 2011).

In the Decision-Theoretic (DT) school of adaptive management, the emphasis is placed on a priori articulation of uncertainty through alternative hypotheses about system response to management and derivation of optimal strategies that solve the "dual-control problem" of achieving long-term management objectives by balancing the benefits and costs of learning in the short term. The DT school is most focused on known unknowns—uncertainty that can be explicitly articulated—and, therefore, advocates adaptive design that seeks resolution of this uncertainty but only to the degree that such resolution will improve future management. Learning is explicitly linked to future management decisions by associating particular courses of action with the degree of evidence in support of the alternative hypotheses; in this way, long-term management is articulated as part of the adaptive program, so the natural transition from experimentation to implementation is specified up front. The tenets of the DT school are arguably a more direct expression of Walters (1986) than other schools of adaptive management. The example most commonly associated with the DT school is the adaptive harvest management of mallards in North America (Johnson and others, 1997).

It seemed appropriate that the 1995 Glen Canyon Dam Final EIS and the GCDAMP embraced an RE school approach to adaptive management. At the time, there was very significant uncertainty about the dynamics of the Colorado River system below Glen Canyon Dam, so an approach that emphasized learning about unknown unknowns made sense. Several policy experiments have been completed, and a great deal has been invested in research; together these have greatly advanced the state of knowledge. It would have been difficult in 1995 to anticipate all the discoveries and specify clearly how and when management of Glen Canyon Dam would move from an experimental phase to a long-term implementation phase. The current question for the joint-lead agencies is if the last two decades of research and experimentation have generated enough knowledge to allow the articulation of uncertainty as known unknowns and pursue a DT school approach to adaptive management. The joint-lead agencies believe this is the case, and approached the development of the LTEMP EIS with this philosophy in mind.

3.3.2 Articulating Uncertainty as Competing Hypotheses

For many, if not all, of the resource goals, the performance of the alternatives is uncertain. Some of that uncertainty can be captured simply by including estimates of variance around the forecasts, but some uncertainty is pervasive enough that it could change the ranking of the alternatives relative to a particular resource goal and, thus, could impede the identification of a preferred alternative. For these critical uncertainties, the SME teams characterized the uncertainty in the predictive models as a set of competing hypotheses. The focus of the uncertainty was on the mechanisms or parameters in the models, not on a holistic statement of uncertainty about whether a particular management intervention will work or not; thus, for example, rather than state the uncertainty as whether or not a particular management alternative will build and sustain beaches, the uncertainty was expressed as competing hypotheses about the long-term rate of sediment input from the Paria River. Likewise, whether trout management flows (TMFs) work or not was expressed as competing hypotheses about the rate of recruitment of juvenile rainbow trout when TMFs are used.

Development of competing hypotheses to capture critical uncertainty is challenging. It requires very deliberative thought about the limits of knowledge and the nature of uncertainty that would affect the ranking of management alternatives. To do so with a small number of discrete hypotheses requires a simplification of the full degree of uncertainty. But careful thought along these lines allows a transparent and explicit statement of the uncertainty that is the focus of experimental and adaptive design. In a NEPA context, such explicit articulation of critical uncertainty allows full disclosure of the motivation for experimental design and explanation of how subsequent management will respond to newfound knowledge.

3.3.3 Deconstructing Complex Alternatives

Several of the alternatives under consideration in the DEIS (especially Alternatives C, D, and E; see explanations of each in the "Alternatives" sections 5.4, 5.5, and 5.6) include, either explicitly or implicitly, complex experimental or adaptive designs (see, for example, figs. 2–13 and 2–14 in Bureau of Reclamation and National Park Service, 2015). These strategies prescribe different management interventions depending on state and information conditions. It is particularly important to distinguish state-dependent triggers from information-dependent triggers. State-dependent triggers are conditions of the state of the system that would lead to implementation of a different management action, primarily in recognition that the Colorado River is a stochastic ecosystem, and it is important to be able to respond to natural variation. Most obviously, all the alternatives contain state-dependent triggers under the Bureau of Reclamation (2007) guidelines that specify, among other parameters, the annual volume for water release from Glen Canyon Dam. Other state-dependent triggers are designed to guard against chance reductions in HBC or other resources of concern. State-dependent triggers are in contrast to information-dependent triggers, which are indications that the state of knowledge has changed substantially and a new approach to management is warranted; for example, Alternatives C and E propose experimental implementation of TMFs, and it is at least implicit in both that if those TMFs are ineffective in reducing downstream migration of rainbow trout from Lees Ferry, they would be discontinued. This is an information-dependent trigger. To the extent possible, information-dependent triggers should be explicit in that they specify the weight of evidence that would be needed on one hypothesis or another to induce a change in management strategy.

A complex experimental or adaptive strategy can be viewed as a portfolio of simpler strategies combined and implemented in a manner to reduce critical uncertainty, with the ultimate intention to implement one of the simpler strategies as the operational standard in the long term. The information-dependent triggers govern the switch between these simpler strategies. To evaluate such a complex design, the first step is to understand what the simpler strategies are; thus, the complex strategies were deconstructed into simpler long-term strategies, each of which might have state-dependent triggers but not information-dependent triggers. In other words, an experimental or adaptive strategy can be viewed as a set of simpler, operational strategies arrayed against a set of competing hypotheses. Resolution of the competing hypotheses would lead to identification of a long-term strategy, but of course, in the short term, an experimental design is needed to achieve that resolution. The first step in development of such a complex strategy is the articulation of the simpler component strategies and the attendant competing hypotheses; the development of the experimental design is a later step.

3.3.4 Value of Information

The essence of the DT school of adaptive management is a focus on uncertainty that is an impediment to the decision maker; that is, resolution of the uncertainty could affect the choice of the long-term management strategy. To evaluate the importance of a source of uncertainty, we used a technique known as the value of information (Raiffa and Schlaifer, 1961; Howard, 1966; Runge and others, 2011b), which was also advocated by Walters (1986) as the motivation for adaptive management. The idea behind the value of information is to compare the expected performance if a decision has to be made in the face of uncertainty with the expected performance if uncertainty can be resolved before committing to a decision. This contrast, known as the EVPI, sets an upper bound on the value of experimental or adaptive management measured on the scale of the management objective(s). To make a decision in the face of uncertainty, a decision maker chooses to implement an action that achieves the highest expected performance against the uncertainties, but that decision carries the risk of being wrong (because some other action could have performed better); the value of information measures how important it is to eliminate that risk. There are two related methods: (1) the expected value of partial information (EVXI) allows calculation of the value of reducing some component of uncertainty, while remaining uncertain about the rest; and (2) the expected value of sample information takes into account the noise in the monitoring.

To calculate the value of information, uncertainty must be explicitly articulated (as competing hypotheses with evidentiary weights or as a probability distribution on a set of parameters). With a small set of competing hypotheses, the calculations involve several steps: (1) forecasting the performance of each long-term strategy under each hypothesis, (2) calculating a weighted performance across hypotheses to identify an optimal decision in the face of uncertainty, (3) calculating the expected performance if uncertainty could be fully resolved before the management alternative was chosen, and then (4) comparing the expected values in steps 2 and 3.

In a single-objective setting, the EVPI is measured on the scale of that objective; thus, it could be expressed, for example, as the expected increase in the probability of persistence of HBC if uncertainty could be resolved before committing to a long-term management strategy. In a multiple-objective setting, EVPI is calculated on the composite utility scale (in which the full array of objectives is weighted); thus, an evaluation of the importance of uncertainty cannot be calculated without first completing a MCDA to understand the value weights on the resource goals. The sequence of assessment matters; the LTEMP EIS process was crafted to accommodate this series of steps. First, the long-term strategies (the elements of the full alternatives broken down into their constituent parts) were analyzed against the array of performance metrics under all the competing hypotheses. Second, using the expected value across hypotheses, MCDA (with input from stakeholders) was used to generate a preliminary weighting of fundamental objectives. Third, with those weights, the individual competing hypotheses were investigated, and the expected value of information (perfect and partial) was calculated.

3.3.5 Experimental and Adaptive Design

The motivation for the EVPI analysis was to provide guidance useful for developing an experimental or adaptive design for implementing management actions, taking into account their value as long-term strategies and the value of reducing uncertainty. This report only describes the results from the decision analysis, with a brief discussion of the implications of the results for experimental design (section 9.2, “Motivation for Adaptive Management”); the development of the experimental design is described in the DEIS.

4 Resource Goals and Performance Metrics

In February 2010, the Assistant Secretary of the Interior asked an ad hoc group of the AMWG to develop a set of DFCs, which were outcomes of fundamental importance that were "achievable through the operation of Glen Canyon Dam, subject to the Law of the River and consistent with the Grand Canyon Protection Act" (Castle, 2010, p. 2) During the next 2 years, this ad hoc group worked with the AMWG and DOI to develop the set of DFCs, which were adopted by the AMWG and recommended to the Secretary of the Interior in February 2012. The set of DFCs formed the basis for the development of the resource goals for the LTEMP EIS. The resource goals express the fundamental objectives for the LTEMP EIS and are described in the nine subsections that follow (4.1 through 4.9).

Associated with the resource goals, the joint-lead agencies developed metrics to evaluate the relative performance of the LTEMP alternatives. These scientifically based performance metrics were developed in a series of workshops among SMEs working on the LTEMP EIS and were revised to incorporate feedback from Cooperating Agencies and other stakeholders. The performance metrics are intended to be objective measures of the performance of alternatives relative to goals for each affected resource being evaluated in the LTEMP EIS. Note that these performance metrics are not the full impacts analysis for the LTEMP EIS. Other sources of quantitative and qualitative information, in addition to the performance metrics, were used to assess the overall and relative performance of alternatives and their constituent elements for the LTEMP EIS. A summary of the performance metrics used in the decision analysis is given in table 1.

4.1 Aquatic Ecology

The resource goals associated with aquatic ecology focused on the persistence of HBC and other native fish, the quality of the rainbow trout (RBT) (*Oncorhynchus mykiss*) fishery, and absence or containment of nonnative aquatic species.

4.1.1 Humpback Chub

Resource Goal.—Meet HBC recovery goals including maintaining a self-sustaining population, spawning habitat, and aggregations in the natural range of the HBC in the Colorado River and its tributaries below the Glen Canyon Dam.

Performance Metric 1.—Expected minimum number of adult (greater than or equal to [≥] 200 millimeters [mm]) HBC in the Little Colorado River population during the LTEMP planning period (20 years).

Performance Metric 2.—Average temperature suitability index (scale 0–1) for HBC at RM 157 (Havasu Creek) and RM 213 (Pumpkin Spring) (fig. 1). The potential for a self-sustaining aggregation of HBC at each of these locations was based on a temperature suitability model that considered how well water temperatures met requirements for important HBC life-history stages (spawning, egg incubation, and growth) using triangular probability functions based on the reported ranges of suitable temperatures for each life-history stage (Valdez and Speas, 2007). The composite temperature suitability index was the geometric mean of the suitability indices for each of the life-history stages.

4.1.2 Other Native Fish

Resource Goal.—Maintain self-sustaining native fish species populations and their habitats in their natural ranges on the Colorado River and its tributaries.

In the analysis for the EIS, temperature suitability indexes for other native fish, similar to the one for HBC, were developed. They did not, however, show much differentiation among alternatives, and they did not differ much from each other and from the HBC temperature suitability metric. These metrics were not, subsequently, used in the decision analysis; the HBC temperature suitability metric was assumed to stand in for other native fish as well.

4.1.3 Rainbow Trout Fishery

Resource Goal.—Achieve a healthy high-quality recreational RBT fishery in the Glen Canyon National Recreation Area and reduce or eliminate downstream RBT migration consistent with NPS fish management and ESA compliance.

Performance Metric 3.—Rainbow trout catch rate in Glen Canyon National Recreation Area (age 2+ fish per angler-hour).

Performance Metric 4.—Rainbow trout emigration rate (number of age-0 RBT moving into Marble Canyon from Glen Canyon per year).

Performance Metric 5.—Abundance of high-quality RBT (greater than [>] 16 inches total length) in the Glen Canyon reach.

4.1.4 Nonnative Aquatic Species

Resource Goal.—Minimize or reduce the presence and expansion of aquatic nonnative invasive species.

In the analysis for the EIS, temperature suitability metrics for nonnative warm-water and cold-water fish and aquatic parasites, similar to the one for HBC, were developed. They did not, however, provide much differentiation among the alternatives. These metrics are reported in the EIS but were not used in the decision analysis.

Table 1. Summary of the 18 performance metrics used in the decision analysis.

[The range for each performance metric captures the amount of variability in the metric because of the effects of the different alternatives, the hydrological and sediment traces, and structural and parametric uncertainty. The range shown was used in the swing-weighting elicitation. HBC, humpback chub; RBT, rainbow trout; #, number; >, greater than]

Number	Resource goal	Performance metric	Units	Desired direction	Range
1	Humpback chub	Minimum number of adult HBC	# adults	Increase	3,000–8,500
2		HBC temperature suitability	Index (0–1)	Increase	0.0–0.2
3	RBT fishery	RBT catch rate	Fish/angler-hour	Increase	1.0–5.0
4		RBT emigration rate	Trout/year	Decrease	15,000–125,000
5		Abundance of high-quality RBT	# fish > 16 inches	Increase	400–1,200
6	Archaeological and cultural resources	Wind transport of sediment index	Index (0–1)	Increase	0.0–0.5
7		Glen Canyon flow index	Days/year	Decrease	0–75
8		Time-off-river index	Index (0–1)	Increase	0.60–0.95
9	Hydropower and energy	Hydropower generation	Million $/year	Increase	120–200
10		Hydropower capacity	Million $/year	Increase	10–50
11	Recreation	Camping area index	Index (0–1)	Increase	0.0–0.5
12		Fluctuation index	Index (0–1)	Increase	0.0–1.0
13		Rafting use index	Visitor-days/year	Decrease	0–1,300
14	Riparian vegetation	Riparian vegetation index	Sum of ratios	Increase	2.0–6.0
15	Sediment	Sand load index	Proportion (0–1)	Increase	0.0–0.6
16	Tribal resources	Marsh vegetation ratio	Ratio	Increase	0.0–1.5
17		Mechanical removal	Years (out of 20)	Decrease	0–5
18		Trout management flows	Years (out of 20)	Decrease	0–20

4.2 Archaeological and Cultural Resources

Resource Goal.—Maintain the integrity of potentially affected National Register of Historic Places eligible or listed historic properties in place, where possible, with preservation methods used on a site-specific basis.

Performance Metric 6.—Wind transport of sediment index (WTSI). This WTSI metric captures the availability of fine sediment for movement by wind. The potential settlement of such sediment over historic properties may provide protection from erosion. The WTSI is the product of the sand load index (SLI; see section 4.7, “Sediment”), which is a proxy for the availability of sediment, and a flow factor, which is higher when low flows happen during the windy season. The WTSI can range between 0 and 1, with higher values indicating more opportunity for transport of sediment.

Performance Metric 7.—Glen Canyon flow index (number of days per year that the maximum daily flow is greater than 23,200 cubic feet per second [ft^3/s]). There are a number of archaeological sites within the Glen Canyon National Recreation Area that could be negatively affected by high flows. Ninemile Terrace is considered representative of other archaeological sites on terraces within the Glen Canyon National Recreation Area; the toe of its slope is at an elevation that corresponds to flows from Glen Canyon Dam of 23,200 ft^3/s.

Performance Metric 8.—Time-off-river index. This metric reflects the availability of discretionary time off river for rafting parties, which allows for greater visitation of archaeological sites. From the standpoint of protection of archaeological and cultural sites, such discretionary time is not desirable. The time-off-river index is calculated from the mean daily flow levels in the river: daily flows less than 10,000 ft^3/s receive a score of 1 (because rafting progress is slow and there is little discretionary time); daily flows greater than 31,500 ft^3/s receive a score of 0 (because rafting progress is fast, allowing the most discretionary time); and daily flows between 10,000 and 31,500 ft^3/s receive a score based on linear interpolation. The daily scores are averaged within seasons: summer (May–August), winter (November–February), and spring and fall (March–April and September–October, respectively). An annual value is calculated using a weighted average across seasons, with higher weight (0.54) given to summer than to spring and fall (0.31) or winter (0.15). The final metric ranges between 0 and 1, with higher values indicating better potential to protect archaeological resources.

4.3 Hydropower and Energy

Resource Goal.—Maintain or increase Glen Canyon Dam electric energy generation, load following capability, and ramp rate capability; and minimize emissions and costs to the greatest extent practicable, consistent with improvement and long-term sustainability of downstream resources.

Performance Metric 9. —Value of hydropower generation (million dollars per year). The value of hydropower energy production over a 20-year trace is discounted at 3.375 percent per year. The total net present value of energy production is divided by 20 to provide an annualized measure.

Performance Metric 10.—Value of hydropower capacity (million dollars per year). The WAPA enters into long-term firm contracts that obligate them to deliver firm electric service to their customers. For the purpose of the LTEMP EIS, the value of these contracts is estimated by first calculating the amount of power (megawatt [MW]) that can be contracted, then multiplying by the replacement cost for that capacity (dollars per MW-year). The capacity itself is calculated by finding the 90-percent exceedance value (10th percentile) for the daily maximum generation in August (August is the month with the highest demand) during a 20-year trace. The replacement cost used was $50,100/MW-year based on a natural gas combustion turbine.

Additional metrics associated with hydropower generation, including the retail rate effects on residential and nonresidential consumers, are examined in the LTEMP EIS but were not available in time to be included as part of the decision analysis.

4.4 Natural Processes

Resource Goal.—Restore, to the extent practicable, ecological patterns and processes within their range of natural variability, including the natural abundance, diversity, and genetic and ecological integrity of the plant and animal species native to those ecosystems.

A quantitative performance metric to capture this resource goal was not developed because of its multifaceted complexity. In the EIS, the alternatives are compared qualitatively against this resource goal, but it was not used in the decision analysis.

4.5 Recreational Experience

Resource Goal.—Maintain and improve the quality of recreational experiences for the users of the Colorado River ecosystem. Recreation includes, but is not limited to, flatwater and whitewater boating, river corridor camping, and angling in Glen Canyon.

Performance Metric 11.—Camping area index. This metric captures the availability of medium (16–25 people) and large (>25 people) campsites on beaches along the Colorado River. The camping area index is the product of the SLI (see section 4.7, "Sediment"), which measures the availability of sediment for beach forming, and a flow factor, which reflects exposure of the beaches. The flow factor is calculated from the maximum daily flows. A score of 1 is given to flows less than 8,000 ft^3/s (because the lower flow means a lower elevation of the water and hence more beach exposure); a score of 0 is given to flows greater than 31,500 ft^3/s; and an intermediate score is determined by linear interpolation for flows between 8,000 and 31,500 ft^3/s. The flow factor is averaged over days within each season, and then over seasons, with higher weight given to the summer season (0.54) than the spring and fall (0.31) or winter (0.15) seasons. The camping area index can range between 0 and 1, with higher values indicating greater availability of medium and large campsites.

Performance Metric 12.—Fluctuation index. This index measures the fraction of time that the daily fluctuations in flow are within a tolerable range; tolerable is defined based on the study by Bishop and others (1987). As the mean daily flow increases, greater fluctuations are tolerable. For mean daily flow in the range from 5,000 to 8,999 ft^3/s, the daily fluctuation index is 1 if the daily fluctuation is less than 3,400 ft^3/s; for daily flow in the range from 9,000 to 15,999 ft^3/s, the fluctuation index is 1 if the daily fluctuation is less than 4,800 ft^3/s; for daily flow in the range from 16,000 to 31,999 ft^3/s, the fluctuation index is 1 if the daily fluctuation is less than 7,200 ft^3/s; and for daily flow greater than 32,000 ft^3/s, the fluctuation index is 1 if the daily fluctuation is less than 9,800 ft^3/s. In all cases, the daily fluctuation index is 0 if the daily fluctuation is greater than 10,000 ft^3/s. For fluctuation index values between 1 and 0, the index is determined by linear interpolation between the tolerable threshold and 10,000 ft^3/s. The daily values for the fluctuation index are averaged within seasons, then averaged across seasons with higher weight (0.54) given to summer months than to spring and fall (0.31) or winter months (0.15). The fluctuation index can range between 0 and 1, with higher values indicating a better visitor experience as influenced by fluctuation in water levels.

Performance Metric 13.—Glen Canyon rafting use metric (average boat seats lost per year because of high-flow experiments [HFEs]). During HFEs and for 2 days before and after, Glen Canyon day-rafting operators cannot take recreational passengers. This metric calculates the average number of boat seats lost per year.

Several other metrics reflecting the recreational experience were analyzed in the LTEMP EIS. In some cases, these did not help to discriminate among the alternatives, and in other cases, these metrics were highly correlated with other metrics. For these reasons, the metrics were not included in the decision analysis and are not described here.

4.6 Riparian Vegetation

Resource Goal.—Maintain native vegetation and wildlife habitat, in various stages of maturity, such that they are diverse, healthy, productive, self-sustaining, and ecologically appropriate.

Performance Metric 14.—Riparian vegetation index. This index summarizes predicted changes during the 20-year LTEMP period in the relative cover of native vegetation community types and the relative diversity of community types, as described by a seven-state state-and-transition model (Ralston and others, 2014). The index is calculated as the sum of four component ratios: the ratio of final to initial native vegetation cover, the ratio of final to initial vegetation state diversity, the ratio of final to initial native to nonnative dominant vegetation state, and the ratio of initial to final cover of arrowweed. An index value of 4.0 indicates an unchanged vegetation condition; values greater than 4.0 indicate improved vegetation conditions; values less than 4.0 indicate degraded vegetation conditions.

4.7 Sediment

Resource Goal.—Increase and retain fine sediment volume, area, and distribution in the Glen, Marble, and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes.

Performance Metric 15.—The SLI (the cumulative sand load transported by high flows [greater than 31,500 ft^3/s] divided by the cumulative sand load transported in total). The range of this metric is 0–1, with higher values reflecting the potential for larger sandbars because more of the sediment is transported at higher river volumes and hence higher elevations. A number of other metrics that summarize the transportation and deposition of sediment were analyzed in the LTEMP EIS. They were all fairly highly correlated; only the SLI was used in the decision analysis.

4.8 Tribal Resources

Resource Goal.—Maintain the diverse values and resources of traditionally associated tribes along the Colorado River corridor through Glen, Marble, and Grand Canyons.

In discussions with tribal representatives during the course of the development of the LTEMP EIS, a large number of important resource goals were identified. A concerted effort was made to understand these goals as clearly as possible, but it was challenging to express some of them in terms amenable to measurement. Although all these goals are important aspects of the importance to the tribes of the Grand Canyon, the Colorado River, and their management, not all of them will be affected by the alternatives being considered in the LTEMP EIS. All of these resource goals are discussed and evaluated in the LTEMP EIS. The full set of goals is described in this section, but only those for which performance metrics were identified are included in the decision analysis.

4.8.1 Health of the Ecosystem

The ecosystem in Glen, Marble, and Grand Canyons is more than the sum of its parts and, in the view of the tribes, should be healthy as a whole. Historically, in the GCDAMP, the overall health of the ecosystem has been examined by evaluating the status of each part, but this reductionist approach might possibly miss some important aspects. There are a variety of indicators of ecosystem health that could be considered including, but not limited to, the following: the health of the river and its ability to sustain life; the color of the water; the absence of contaminants, pollutants, and disease in the water; the potability of the water; the quality of the water that reaches Lake Mead; and the viability and health of wildlife and plants in Glen, Marble, and Grand Canyons. It is important to understand that, for many tribes, the Colorado River is a sentient being and the spiritual center of the ecosystem because it has the capability of giving and taking life and is prone to anger if mistreated. The health of the ecosystem depends on the health of the Colorado River.

Because of the holistic nature of this resource goal, it was difficult to find a single performance metric that summarized it. A narrative analysis of this resource goal is found in the LTEMP EIS, but it was not included in the decision analysis.

4.8.2 Sites of Cultural Importance

There are specific sites within Glen, Marble, and Grand Canyons that are important for cultural reasons; and for preservation of tribal, religious society, kiva group, and clan history (for example, shrines, sacred sites, ancient burial sites, springs, plant collection areas, mineral collection areas, offering places, and other elements). These sites can be threatened by erosion, loss of sediment inputs, and intrusive human use (especially nontribal, outside visitors). Flow and nonflow actions (for example, education, permitting, research and monitoring, and interpretation) may affect these sites.

Performance Metric 16.—Marsh vegetation ratio (ratio of frequency of wetland states during the course of 20 years to frequency of wetland states if the initial abundance remained unchanged). Wetlands are a rare and important habitat type along the Colorado River; within Glen, Marble, and Grand Canyons, there are currently approximately 4.6 acres of such habitat. Maintenance and increase of marsh vegetation is important from a tribal perspective. The metric is calculated by looking at the marsh and shrub wetland states in the riparian state-and-transition model (Ralston and others, 2014) during the course of a 20-year projection and comparing that to the current abundance. The metric is a ratio; thus, a value of 1.0 indicates an unchanged abundance of marsh (on average), a value greater than 1.0 indicates an average increase, and a value less than 1.0 indicates an average decrease.

A number of aspects of this resource goal are also reflected in other performance metrics described in previous sections. The WTSI (performance metric 6) focuses on the availability of fine sediment for transfer to protect National

Register eligible or listed sites. Such sites, however, do not represent the full set of places of tribal concern, so other metrics must also be considered. The Glen Canyon flow index (performance metric 7) reflects the protection of some important sites in Glen Canyon. The time-off-river index (performance metric 8) measures the degree to which the discretionary time off river of rafters might affect cultural resources, including those of tribal importance.

In additions to these performance metrics, a number of other considerations are evaluated narratively in the LTEMP EIS, including riparian vegetation diversity, native fish diversity, and access to springs.

4.8.3 Respect for Life

To many of the tribes associated with the Colorado River and Glen, Marble, and Grand Canyons, life itself is sacred. Human activities should protect and promote life, not destroy it. There are two aspects to this resource goal: first, minimize the taking of life; and second, encourage the expansion and proliferation of life. These are both complex concepts. The tribes recognize that it is appropriate for humans to take other life in some circumstances, especially when it promotes other life (particularly, our own consumption for survival), but this taking needs to be minimal and respectful because there are spiritual consequences associated with the taking of life. The promotion of life is also important but does not necessarily imply a return to historical or "natural" conditions. The Glen Canyon Dam has encouraged new life in Glen, Marble, and Grand Canyons, so a return to predam conditions is not necessarily implied by this objective. It is worth noting that many of the tribes do not make a strong distinction between native and nonnative species.

Performance Metric 17.—Frequency of mechanical removal, as measured by the average number of years in which trout mechanical removal trips happen. Several of the alternatives considered in the LTEMP EIS include the use of electrofishing and removal of nonnative trout at the confluence of the Colorado River with the Little Colorado River in an effort to reduce the piscivory of juvenile HBC by trout. A number of tribes, especially Hopi and Zuni, have raised concerns about this taking of life. As a coarse measure of the cultural, spiritual, and ethical effects of killing trout, this performance metric allows distinctions among alternatives, favoring those that make an effort to minimize mechanical removal. But the nature of the take, the purpose behind it, the methods of the take, the disposition of the trout taken, and the mind set of those killing the fish all also affect the sacred treatment of living beings.

Performance Metric 18.—Frequency of trout management flows, as measured by the average number of years in which TMFs happen. Several of the alternatives considered in the LTEMP EIS include the potential for use of TMFs. The TMFs, designed to reduce reproduction or survival of juvenile trout, are considered to be killing by some tribes and should be minimized. Alternatives that include TMFs are likely to differ in how often the flows are triggered, so this performance metric helps to distinguish among the alternatives.

4.8.4 Sacred Integrity of Grand, Marble, and Glen Canyons

Glen, Marble, and Grand Canyons are sacred to many tribes, and the preservation of their sacred integrity is important. The sanctity of Glen, Marble, and Grand Canyons may be threatened by human activities and behaviors, development, and the presence of artificial structures and activities. An important aspect of the sanctity is the intentionality of visitors: when outsiders enter Glen, Marble, and Grand Canyons (on boat or hiking trips), the respect they show to the canyons and Colorado River can affect the spiritual integrity. There are many consequences of the disturbance of this sanctity, including, but not limited to, the following: a reduction of the spiritual strength of plants gathered and used by the Navajo for medicinal and cultural purposes; an inability to retire Navajo sacred objects into the Colorado River when they have become too old for continued use; weakening of the sacred role the canyons play as a final resting place for Hopi; and an overall disruption of the state of mind and spirit of Zuni religious leaders and of their experience of being within a very sacred place that embodies the Zuni emergence, migrations, and communion with the spirits of Zuni ancestors.

This resource goal, although of profound importance to the tribes, is not thought to differ measurably across the alternatives under consideration in the LTEMP EIS because it is not driven by flow operations from Glen Canyon Dam or currently envisioned attendant activities. This goal is evaluated in the narrative EIS analysis but not in the formal decision analysis.

4.8.5 Stewardship

According to their traditions, several of the tribes understand that they have been given a sacred stewardship responsibility for the preservation and harmony of the world; for example, the Hopi have a covenant with the caretaker of this world, Masaw, to be stewards of the earth; other Tribes have similar stewardship ethics grounded in spiritual traditions. To maintain these stewardship responsibilities, the tribes need to be an active part of stewardship of the Glen, Marble, and Grand Canyons. This stewardship includes the following: ceremonial activities, whether performed in the canyons or in the villages; participation in management of the canyons, including water management, through traditional practices and western management activities; and education to maintain cultural knowledge and connection with the canyons. The tribes note that the Federal government also has stewardship responsibilities that arise out of Federal legislation; because Federal involvement has sometimes taken stewardship responsibility from the tribes, it is critical that the Federal government be accountable for its stewardship. At times, some tribes believe the presence of the Federal government has made it more difficult for them to carry out their stewardship responsibilities. Successful development of joint stewardship among the tribes and Federal government will require continued building of mutual respect and trust between those entities.

Tribal stewardship opportunities are not tied to individual alternatives being considered in the LTEMP EIS but could be crafted to apply to any of the alternatives; thus, this resource goal, although of critical importance to the tribes individually and to the ongoing relationship between the tribes and Federal government, may not help distinguish among the alternatives. This goal is evaluated in the narrative EIS analysis but not in the formal decision analysis.

4.8.6 Tribal Connections to the Canyons

The spiritual, historical, and cultural connections that tribes have to Glen, Marble, and Grand Canyons require the protection of sacred sites and the integrity of the canyons as a whole, but protection alone is not enough. The tribes also need opportunities for access, education, and stewardship to keep their connections vibrant. Access can be undermined by physical barriers and by the effects of human activity that decrease the power of those sites and the experience when at them (for example, lack of privacy, disturbance of the soundscape, and viewshed).

Like the sacred integrity and stewardship resource goals, this resource goal is not thought to differ across the alternatives. The flow operations of Glen Canyon Dam are not likely to affect tribal access, education, spiritual ceremonies, or other connections to Glen, Marble, and Grand Canyons. This resource goal may be more appropriately addressed through government-to-government consultation in other forums. This goal is evaluated in the narrative EIS analysis but not in the formal decision analysis.

4.8.7 Economic Opportunity

The Glen, Marble, and Grand Canyons, Colorado River, and Glen Canyon Dam are sources of economic benefit for the tribes in the area. The canyons provide tourism and other opportunities that enhance the economic well-being of tribes. (As an important note, tourism can also undermine the well-being of tribes in aspects other than economic; see the other tribal resource goals.) The Glen Canyon Dam provides affordable electricity for tribal needs and for development projects.

The hydroelectric performance metrics (especially hydroelectric generation, performance metric 9) may reflect one aspect of economic opportunity in that provision of affordable hydroelectricity is a component of economic development. Other economic effects are evaluated in the narrative EIS but were not included in the formal decision analysis.

4.8.8 Tribal Water Rights and Supply

Tribes in the area depend on the Colorado River for many of their water needs; so the preservation of established, traditional, and desired water rights, now and into the future, is important to them. There are a number of claims to water rights that have been asserted by the tribes but for which there are not yet quantified rights through decree or negotiated settlement; some Tribes have indicated that these claims to water rights are as important as established water rights.

Based on its purpose and need, the LTEMP EIS was not intended to include any alternative that violated agreed-upon water rights. The effect of the Lake Powell water elevation on Navajo access to water was examined and was not determined to differ across alternatives.

4.8.9 Process Objectives

The tribes also expressed several important process objectives—objectives that govern how the LTEMP decision is made, rather than what decision is made. The first of these is the genuine incorporation of tribal input to the LTEMP process as a reflection of Federal trust responsibilities. The second is the importance of incorporating learning to improve management with time; in this spirit, an experimental approach that can result in adaptive management is favored.

Because these were process objectives, they were not evaluated in the formal decision analysis, which focused on objectives that could help discern among the alternatives.

4.9 Water Delivery

Resource Goal.—Ensure that water delivery continues in a manner that is fully consistent with and subject to the Colorado River Compact, Upper Colorado River Basin Compact, Water Treaty of 1944 with Mexico, decree of the Supreme Court in *Arizona* v. *California*, and provisions of the Colorado River Storage Project Act of 1956 and the Colorado River Basin Project Act of 1968 that govern allocation, appropriation, development, and exportation of the waters of the Colorado River Basin; and consistent with applicable determinations of annual water release volumes from Glen Canyon Dam made pursuant to the Long-Range Operating Criteria for Colorado River Basin Reservoirs, which are currently implemented through the 2007 interim guidelines (Bureau of Reclamation, 2007).

The scope and need of the LTEMP EIS was designed to preserve existing agreements concerning water delivery; thus, none of the alternatives considered were meant to differ with regard to aspects of water delivery. A number of water delivery metrics were evaluated to make certain that this part of the purpose and need was upheld. None of the alternatives were determined to differ with regard to these metrics; thus, they were not included in the decision analysis.

5 Alternatives

Seven alternatives were considered in the LTEMP EIS. Each of these alternatives is a complex combination of flow and nonflow actions, often with condition-dependent and information-dependent triggers for various components. Four of the alternatives (B, C, D, and E) also contain variants (called long-term strategies) to represent different combinations of actions that would be taken once critical uncertainties were resolved. In total, 19 long-term strategies were evaluated. A brief summary of these alternatives is given here to provide context for the decision analysis with an emphasis on those elements that differ across alternatives. A full description of these alternatives, with the rationale for each, is given in chapter 2 of the LTEMP EIS.

5.1 Action Elements

The alternatives are composed of flow actions, which govern how water flow through Glen Canyon Dam is to be managed on hourly, daily, and monthly scales, as well as nonflow actions, which govern other activities meant to complement the flow actions to achieve the resource goals.

5.1.1 Monthly Release Pattern and Other Base Operations

The seven alternatives differ in the operational characteristics that govern flow through Glen Canyon Dam (table 2). All alternatives follow the 2007 interim guidelines (Bureau of Reclamation, 2007), which specifies the annual volume of water to be passed through Glen Canyon Dam. The alternatives differ in how they apportion the annual volume to monthly volumes, ranging from patterns that match releases under the previous EIS to patterns that match monthly demand for electricity to patterns that approximate the unregulated flow in the Colorado River. The minimum flow at any time differs across alternatives, with a range from 5,000 to 8,000 ft^3/s. The maximum flow for base operations is the same for all alternatives (25,000 ft^3/s). The daily range specifies the limit to how much variation there can be between the minimum and maximum flow on a given day and ranges between 0 and 12,000 ft^3/s across alternatives. The ramp rates limit how quickly the flow can change; for all alternatives the ramp rate for increasing flow is 4,000 cubic feet per second per hour (ft^3/s-h); the ramp rate for decreasing flow is lower, ranging from 1,500 to 4,000 ft^3/s-h.

5.1.2 High-Flow Experiments

Since 1996, there have been a number of experimental high-flow releases of water through Glen Canyon Dam, designed to mimic natural high flows and deposit sediment at higher elevations, in an effort to rebuild sandbars and restore other ecosystem processes in Glen, Marble, and Grand Canyons. High-flow releases exceed the operational maximum daily flow and can be as high as 45,000 ft^3/s depending on the number of generation units available. The Bureau of Reclamation (2011a) established a protocol for determining when HFE releases were warranted and how they should be implemented. To date, the HFEs that have been implemented under the 2011 HFE protocol have happened in the fall, although the HFE protocol allows them to happen in the spring after 2015. The LTEMP EIS alternatives differ in if, when, and how they allow fall HFEs and spring HFEs (table 3). In addition, some of the alternatives allow proactive spring HFEs; these are HFE releases designed to protect sand supply in years when the annual guidelines call for high annual volumes (>10 million acre-feet). Most of the HFEs are limited to a maximum duration of 96 hours, but some of the alternatives allow extended-duration HFEs if adequate sediment supply is available (table 3).

5.1.3 Trout Management Flows

High flows, whether through high annual volumes or HFEs, have been determined to increase RBT production in the Glen Canyon reach. Because of the concern about the effect of RBT on HBC, methods have been sought to manage RBT populations. One proposed method is TMFs. These are patterns of high-water release (for example, 20,000 ft^3/s) for 2–7 days to encourage young-of-the-year trout to move to higher elevation shallow-water habitats followed by a rapid drop to a low flow (for example, 5,000 to 8,000 ft^3/s) during the day to strand young trout and expose them to sunlight and heat. The intention is to reduce RBT production and, hence, reduce emigration of trout from Glen to Marble Canyon, lowering the risk to HBC farther downstream. The TMFs have not previously been implemented at Glen Canyon Dam. They are considered an experimental element in several of the alternatives (table 3).

5.1.4 Other Flow Manipulations

A variety of other flow manipulations are built into the alternatives. Low summer flows are designed to produce warmer conditions for juvenile HBC growth in the Colorado River at the confluence with the Little Colorado River by reducing flows from July through September. These flows would be implemented experimentally in those alternatives that allow them (table 3).

Sustained low flows for benthic invertebrate production ("bug flows") are an experimental action considered under Alternative D for restoring mayflies, stoneflies, and caddisflies to Glen and Marble Canyons. If implemented, steady minimum flows would be provided every weekend from May through August, to ensure that eggs laid during weekends would not be subject to drying because of lower water levels during egg development. Demand for electricity is lower on

Table 2. Operational characteristics of Long-Term Experimental and Management Plan alternatives.

[maf,, megaacre-foot; kaf, kiloacre-foot; ft³/s, cubic foot per second; >, greater than]

Elements of base operations	Alternative						
	A	B	C	D	E	F	G
Monthly pattern in release volume	Historic monthly release volumes.	Same as Alternative A	Highest volume in high electric demand months; February–June volumes proportional to contract rate of delivery; lower volumes August–November	Comparable to Alternative E, but August and September volume increased, with additional volume taken from January through July	Monthly volumes proportional to the contract rate of delivery, but with a targeted reduction in August–October volumes; volume released in October, November, and December=2.0 maf in > 8.23-maf years	Relative to Alternative A, higher release volumes in April–June; lower volumes in remaining months	Equal monthly volumes, adjusted with changes in runoff forecast.
Minimum flows (ft^3/s)	8,000 during day; 5,000 during night	Same as Alternative A	Same as Alternative A	Same as Alternative A	Same as Alternative A	5,000	5,000
Maximum flows (ft^3/s)	25,000	Same as Alternative A	Same as Alternative A	Same as Alternative A	Same as Alternative A	Same as Alternative A	Same as Alternative A.
Daily range (ft^3/s)	5,000, 6,000, or 8,000 depending on monthly volume	December and January: 12,000 February, July, and August: 10,000 October, November, March, June, and September: 8,000 April and May: 6,000	Equal to 7 × monthly volume in kaf in all months; 2,000 ft^3/s following significant sediment input in summer or fall	Equal to 10 × monthly volume in kaf in June–August, and 9 × monthly volume in kaf in other months; not to exceed 8,000 ft^3/s	Equal to 12 × monthly volume in kaf in June–August, and 10 × monthly volume in kaf in other months; 2,000 ft^3/s following significant sediment input in summer or fall	0	0
Ramp rates (ft^3/s-hr)	4,000 up 1,500 down	4,000 up 4,000 down November–March 3,000 down in other months	4,000 up 2,500 down	4,000 up 2,500 down	4,000 up 2,500 down	4,000 up 1,500 down	4,000 up 1,500 down.

Table 3. Triggered and experimental elements of the Long-Term Experimental and Management Plan long-term strategies.

[A filled circle (●) indicates the element in question is implemented fully in the long-term strategy; an open circle (○) indicates the element in question is implemented in some partial degree; and -- indicates that element is not part of that long-term strategy. HFE, high-flow experiment]

Element	Alternative																		
	A	B		C				D				E						F	G
	A	B1	B2	C1	C2	C3	C4	D1	D2	D3	D4	E1	E2	E3	E4	E5	E6	F	G
Fall HFEs	○	○	○	●	●	--	●	●	●	●	●	●	●	--	●	--	--	●	●
Spring HFEs	○	○	○	●	●	--	--	○	○	○	○	○	○	--	--	--	--	●	●
Proactive spring HFEs	--	--	--	●	●	--	--	●	●	●	●	--	--	--	--	--	--	--	●
HFEs longer than 96-hour duration	--	--	--	●	●	--	●	○	○	○	○	--	--	--	--	--	--	--	●
Trout management flows	--	●	●	●	--	--	--	●	●	--	●	●	--	--	--	--	●	--	●
Low summer flows	--	--	--	--	●	--	--	○	○	○	--	--	●	--	--	●	--	--	--
Bug flows	--	--	--	--	--	--	--	--	●	--	--	--	--	--	--	--	--	--	--
Hydropower improvement flows	--	--	●	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Steady flows before HFEs	--	--	--	●	●	--	●	●	●	●	●	●	●	--	●	--	--	●	●
Steady flows after HFEs	--	--	--	●	●	--	●	●	●	●	●	--	--	--	--	--	--	●	●
Mechanical trout removal	●	●	●	--	--	●	●	●	●	●	●	--	--	●	●	--	--	--	●

weekends, so timing the benthic invertebrate production flows during the weekends minimizes the effect on the value of hydropower generation.

Hydropower improvement flows are an experimental action considered under Alternative B to increase hydropower generation during high-demand months (December–February and June–August) in years when the annual volume is less than or equal to (≤) 8.23 million acre-feet. These flows work largely by allowing a greater daily range and higher ramp rates.

Some of the alternatives use steady flows before an HFE to conserve sediment for the high-flow release, after an HFE to reduce erosion of newly built sandbars, or both (table 3). These steady flows stop the load-following patterns of hourly releases and are sometimes called “load-following curtailment.”

5.1.5 Nonflow Actions

Under a 2011 assessment (Bureau of Reclamation, 2011b), experimental methods of controlling trout populations were evaluated and implemented. These methods include mechanical removal of brown trout (*Salmo trutta*) and RBT at the Little Colorado River through electrofishing, selective removal, and beneficial use of the fish removed. Many of the LTEMP EIS alternatives allow for continued use of mechanical removal with specific requirements for when such removal would be triggered (table 3).

Under all alternatives except Alternative A (no-action alternative), the NPS would implement experimental vegetation restoration to modify the cover and distribution of plant communities along the Colorado River. This restoration would include removal of nonnative species, prevention of new introductions, planting of native species, management of vegetation at campsites, and removal of windrows that block wind transport of sediment.

5.1.6 Long-Term Strategies

Four of the seven alternatives (Alternatives B, C, D, and E) were conceived as experimental and adaptive strategies, with elements that would be deployed experimentally to allow resolution of uncertainty and subsequent adaptation of the strategy in response to the information acquired; thus, within each of these alternatives are a number of implicit long-term strategies that might result after resolution of uncertainty. Not all of those possible long-term strategies were analyzed, but a representative set from each alternative was articulated and analyzed to capture the possible range of environmental effects and evaluate the importance of resolving the underlying uncertainty; thus, for example, under Alternative C, whether or not to implement fall HFEs, spring HFEs, TMFs, low summer flows, or mechanical removal will depend on the efficacy of those actions in achieving their intended purpose, the strengths of undesirable side effects of those actions, and the underlying effect of RBT on HBC. The long-term strategies C1, C2, C3, and C4 represent a range of possible solutions once such uncertainty is resolved; if, for instance, spring HFEs have a beneficial effect on sediment deposition and only a small effect on RBT production, TMFs are ineffective, but low summer flows benefit HBC, then long-term strategy C2 might be the best version of Alternative C to use. All of the 19 long-term strategies (table 3) were evaluated against the critical uncertainties described in sections 6.2.1, 6.3.1, and 6.5.1.

5.2 Alternative A (No Action)

Alternative A, the no-action alternative, represents continued operation of Glen Canyon Dam under the existing guidelines in Bureau of Reclamation (1996), interim guidelines in Bureau of Reclamation (2007), and the two 2011 EAs (Bureau of Reclamation, 2011a, 2011b), as well as other applicable guidance. This alternative has a base operation pattern that was called MLFF in Bureau of Reclamation (1996). Both of the 2011 EAs expire after 2020, so the elements specified in them (HFEs and mechanical removal) would cease at that point (Bureau of Reclamation 2011a, 2011b). Beyond the actions discussed in Bureau of Reclamation (2011a, 2011b), there are limited experimental options that can be tested under this alternative.

5.3 Alternative B

Alternative B was designed to increase the value of hydropower generation while limiting negative effects to other resources. This alternative was submitted by the Colorado River Energy Distributors Association (CREDA), a member of AMWG. The base operations are designed to generate more valuable power than Alternative A by increasing the daily range and ramp rates to allow power generation to more closely follow power demand. This alternative limits the implementation of HFEs to one every other year because HFEs release water without generating power and require water volumes to be shifted from months when the value of power is potentially higher to other months. To moderate some of the negative effects of this water-release pattern on other resources, Alternative B includes mechanical removal, evaluation of TMFs, and experimental implementation of vegetation restoration.

5.3.1 Alternative Long-Term Strategies

Alternative B includes two long-term strategies, one with its base operations (B1) and one that includes hydropower improvement flows (B2), maximum power plant capacity flows implemented as many as four times during the LTEMP period, in years when the annual volume is ≤8.23 million acre-feet (table 3). Such years, because of their lower volume of release, typically require the most purchases by WAPA to meet contractual demand, so the higher flows could mitigate costly purchases in high-demand months. Whether B1 or B2 is a better long-term strategy, when the effects across all resource goals are taken into account, depends on the strength of negative effects of greater power generation on other resources. Specific hypotheses for these negative effects, which are uncertain, were not explicitly articulated when Alternative B was submitted. The long-term strategies B1 and B2 were evaluated, however, against the set of uncertainties developed in the context of other alternatives.

5.4 Alternative C

Alternative C was developed by the joint-lead agencies to maintain or improve multiple resources, with some priority placed on HBC, sediment, and hydropower. Called the "condition-dependent adaptive strategy" in interim public documents during the preparation of the EIS (Bureau of Reclamation and National Park Service, 2014), Alternative C has information-dependent and condition-dependent triggers, seeks to test critical hypotheses, and contains explicit instructions for how new insights will affect subsequent implementation of action elements.

Compared to many of the other alternatives, the base operations for Alternative C shift monthly volumes from the monsoon months (August through November) to high-demands months (December, January, and July) to reduce sediment transport during the monsoonal high-sediment-input period and limit effects on the value of power generation. The reduced volume in late summer is also intended to provide warmer river temperatures for the benefit of HBC and other native fish.

Alternative C includes a number of condition-dependent (triggered) elements; among them are fall HFEs, spring HFEs, proactive spring HFEs, extended duration HFEs, TMFs, low summer flows, load-following curtailment, and mechanical removal of trout. The specific details of the triggers for these events are found in chapter 2 of the EIS. Most of these elements are experimental, and so there are information-dependent triggers as well; that is, monitoring and evaluation of all these elements would be completed, and elements would be dropped or retained depending on if the evidence supported their retention.

5.4.1 Alternative Long-Term Strategies

Four long-term strategies (C1, C2, C3, and C4) were developed to capture the range of possible outcomes from adaptive implementation of Alternative C (table 3). The motivation for the creation of these long-term strategies was the recognition that there are critical uncertainties that impede identification of the best long-term strategy. The key questions concerned the following: the magnitude of increase in RBT production in the Glen Canyon reach caused by fall HFEs, the relative effects of temperature and trout density on survival and growth of juvenile HBC at the Little Colorado River, and the effectiveness of TMFs in reducing RBT production. The relevance of these uncertainties arises because of the possible tradeoffs among the objectives of supporting the HBC population, maintaining a strong rainbow trout fishery, increasing sediment deposition and sandbar building, and affirming tribal values concerning the respect for life (especially aquatic life). Each of the action elements under consideration (HFEs, TMFs, low summer flows, and mechanical removal) is meant to increase achievement of one or more of those objectives, but the question is if the benefits to one objective come at the expense of others. Alternative C was designed under the assumption that the best mix of action elements (the best long-term strategy) depends on resolution of the critical uncertainties.

Long-term strategy C1 allows use of all the triggered elements from Alternative C except for low summer flows and mechanical removals; such a strategy has been hypothesized to be warranted, for instance, if the effect of spring HFEs on trout production was weak, TMFs were effective, and low summer flows were not effective. Long-term strategy C2 is similar to C1 except that it calls for low summer flows but not TMFs. Long-term strategy C3 does not allow HFEs and might be called for if HFEs are determined to cause a very strong increase in trout recruitment and other actions are ineffective at mitigating the effect of trout on HBC. Long-term strategy C4 allows fall HFEs but not spring HFEs and manages the effect of trout on HBC through mechanical removal.

Whether or not the resolution of the critical uncertainties actually matters to the ranking of the long-term strategies is one of the central questions in section 8.3, "Expected Value of Information."

5.5 Alternative D

Alternative D was developed by the joint-lead agencies after a full analysis of the other six LTEMP alternatives had been completed. The initial analysis suggested that there were strong characteristics of Alternatives C and E that contributed to achievement of resource goals and motivated creative thinking about how to achieve more of those benefits in a single alternative. Alternative D adopts characteristics of Alternatives C and E.

The base operations for Alternative D are in many respects a compromise between those of Alternatives C and E (table 2). The monthly pattern of release is most similar to that of Alternative E, with an increase in the August and September volumes (and a corresponding decrease in the January through June volumes). The daily range for flows is about midway between the ranges from Alternatives C and E.

The experimental and adaptive options for Alternative D include all the elements considered in the any of the alternatives, except for hydropower improvement flows (table 3). The experimental implementation calls for early testing of TMFs in the first 2–5 years without having to meet the condition-dependent triggers and delayed consideration of spring HFEs until the third year of implementation.

5.5.1 Alternative Long-Term Strategies

Four long-term strategies (D1, D2, D3, and D4) were developed to capture the range of possible outcomes from adaptive implementation of Alternative D (table 3). The long-term strategies in this set look more similar than in the sets for Alternatives C and E because they were created after an initial analysis of the other six alternatives and, thus, reflect insights from that analysis. For instance, long-term strategies D1 through D4 are all similar with regard to implementation of HFEs because the initial analysis suggested that the benefits of HFEs outweighed the costs, even in the face of the uncertainties tested. There remain, however, other long-term strategies implicit in Alternative D; for example, if spring, proactive, or extended HFEs are determined to have very strong negative effects on resources of importance that cannot be mitigated by other actions, they could be removed from long-term implementation. The four long-term strategies for Alternative D, however, are thought to capture the most important differences that might arise in long-term implementation.

Long-term strategy D4 might be considered the base strategy under Alternative D because all action elements except low summer flows and bug flows are in operation (table 3). Long-term strategy D1 adds low summer flows. Long-term strategy D2 adds implementation of bug flows and would be supported if early experimental tests of bug flows determined they had the intended effects in restoring important native benthic invertebrate communities without having adverse effects on other resources. Under this long-term strategy, low summer flows would only be implemented in the second 10 years. Long-term strategy D3 is similar to D1 but removes TMFs.

The motivations for the different long-term strategies in Alternative D are the same critical uncertainties that motivate the long-term strategies in Alternative C, with a specific focus on the effectiveness of TMFs, the influence of temperature on juvenile HBC growth and survival, and the effect of bug flows on other resources.

5.6 Alternative E

Alternative E was developed by representatives of the seven states in the Colorado River Basin to provide for recovery of HBC while protecting other important resources, including sediment, the RBT fishery at Lees Ferry, aquatic food base, and hydropower resources. Called the "resource-targeted condition-dependent" strategy in interim public documents during the preparation of the EIS (Bureau of Reclamation and National Park Service, 2014), Alternative E has information-dependent and condition-dependent triggers, seeks to test critical hypotheses, and contains explicit instructions for how new insights will affect subsequent implementation of action elements.

The base operations for Alternative E seek greater value of hydropower production than Alternatives C and D (table 2). The monthly volumes largely follow hydropower demand and are proportional to the contract rate of delivery but with a reduction in August through October volumes to conserve sediment during the monsoon period. The daily range is large compared to the other alternatives. The ramp rates are the same as in Alternative C and D.

Alternative E includes a number of condition-dependent (triggered) elements; among them are fall HFEs, spring HFEs, TMFs, low summer flows, load-following curtailment (before but not after HFEs), and mechanical removal of trout (table 3). Implementation of spring HFEs is delayed until the second 10 years to allow testing of TMFs in the early years (with long-term implementation of spring HFEs conditional on TMFs being an effective tool). An important experimental element of Alternative E is early testing of the response of RBT populations to TMFs and fall HFEs in a 2x2 factorial design, replicated two to three times (in hopes of experiencing both cold and warm water temperatures). The specific details of the triggers for these events are found in chapter 2 of the EIS. Most of these elements are experimental, and so there are information-dependent triggers as well; that is, monitoring and evaluation of all these elements would be completed, and elements would be dropped or retained depending on if the evidence supported their retention.

5.6.1 Alternative Long-Term Strategies

Six long-term strategies (E1, E2, E3, E4, E5, and E6) were developed to capture the range of possible outcomes from adaptive implementation of Alternative E (table 3). The motivation for the creation of these long-term strategies was the recognition that there are critical uncertainties that impede identification of the best long-term strategy. The key questions concerned the following: the magnitude of increase in RBT production in the Glen Canyon reach caused by fall HFEs, the relative effects of temperature and trout density on survival and growth of juvenile HBC at the Little Colorado River, the effectiveness of TMFs in reducing RBT production, and the effect of high flows on sediment retention.

Long-term strategy E1 uses spring and fall HFEs when triggered, along with TMFs to manage the trout populations; this long-term strategy would be favored, for example, if HFEs are determined to be beneficial to sediment conservation and TMFs are effective in controlling trout populations. Long-term strategy E2 also uses spring and fall HFEs but uses low summer flows instead of TMFs; this strategy might be favored if temperature is a more important factor in HBC survival than trout predation and TMFs are ineffective. Long-term strategy E3 does not allow HFEs, TMFs, or low summer flows and uses mechanical removal to manage trout density at the Little Colorado River when needed; such a strategy might be favored if HFEs greatly increase production of trout, TMFs are ineffective in managing trout populations, HBC are strongly affected by trout predation, and low summer flows do not provide enough advantage to HBC to warrant use. Long-term strategy E4 allows fall HFEs but not spring HFEs and relies on mechanical removal to manage trout at the Little Colorado River. Long-term strategy E5 is like E3 in not allowing HFEs but uses low summer flows rather than mechanical removal to support HBC population growth. Long-term strategy E6 also does not use HFEs and uses TMFs when needed to manage trout. As with Alternatives C and D, these long-term strategies are not meant to be a comprehensive set of the possible permutations of Alternative E that might arise from adaptive implementation but, rather, are meant to represent a broad range of possible outcomes, effectively bracketing the strategies that might arise.

As with Alternative C and D, whether or not the resolution of the critical uncertainties actually matters to the ranking of the long-term strategies is one of the central questions in section 8.3, “Expected Value of Information.”

5.7 Alternative F

Alternative F was designed to follow a more natural pattern of flows, limiting sediment transport and providing warmer temperatures in the summer months. The base operations provide higher release volumes in April–June (to mimic spring runoff), including a May 1 high-flow spike of 45,000 ft^3/s (essentially an untriggered HFE) and lower volumes the remainder of the year. The daily flows are steady with no daily fluctuations (no hydropeaking). The only modification to base operations would be sediment-triggered HFEs (fall and spring). In keeping with the desire to have this alternative better match predam conditions than the other alternatives, it does not use TMFs or mechanical removal.

5.8 Alternative G

Alternative G was designed to maximize the conservation of sediment by providing year-round steady flows. The base operations provide equal monthly volumes and steady daily flows. In practice, the monthly volumes would have to be adjusted as the forecasts for annual volume change through the year, but the intent is to keep flows quite steady. This alternative does allow all forms of HFEs to be used to maximize sandbar building and sediment conservation.

6 Quantitative Methods

The 19 long-term strategies were evaluated against the 18 performance metrics and 5 sources of uncertainty: the hydrology during the 20-year LTEMP period of performance, the sediment inputs during the 20-year LTEMP period of performance, the relative effects of temperature and trout predation on juvenile HBC survival and growth, the effectiveness of trout management flows, and the effect of fall HFEs on trout recruitment. A total of 10 modeling teams built a linked set of analyses to simulate the performance of the long-term strategies; the performance metrics were calculated from the simulation outputs. This section describes the methods used to complete these analyses.

6.1 Modeling Overview

The basis of the analysis of the alternatives was a large, linked set of simulation models that were meant to represent the Colorado River ecosystem below Glen Canyon Dam (fig. 2).

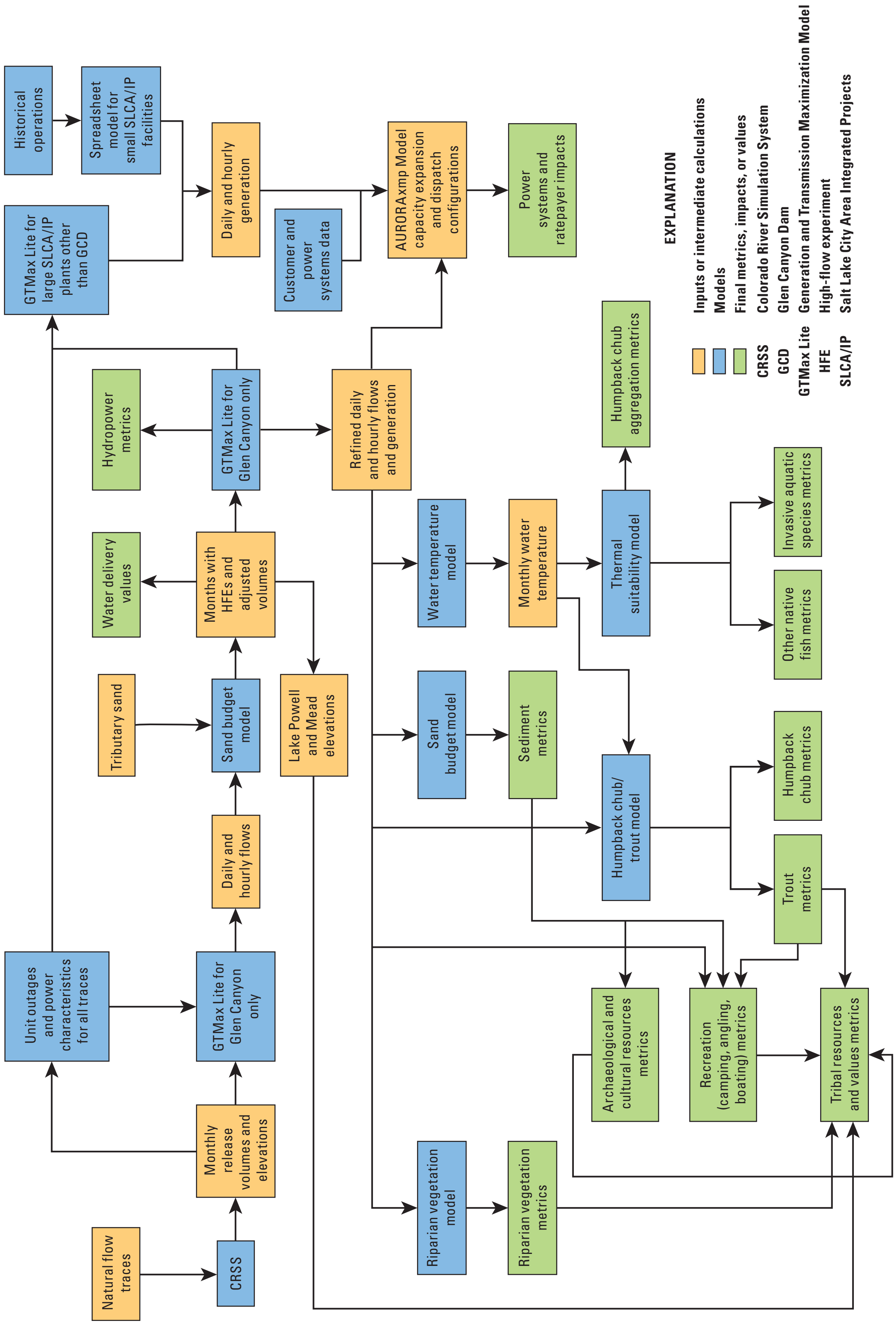

Figure 2. Model flow for the analysis of the Long-Term Experimental and Management Plan long-term strategies against the performance metrics.

Each long-term strategy encoded a set of rules that governed annual, monthly, daily, and hourly flow through the dam, as well as mechanical removal of nonnative fish from the Colorado River at its confluence with the Little Colorado River and vegetation treatments along the river corridor. The long-term strategy, coupled with 21 hydrological traces and 3 sediment traces (to represent environmental variation), determined the flows through the Glen Canyon Dam. The daily and hourly flows then were sent to models for vegetation, sediment, and temperature. The temperature and flow outputs then informed models for RBT, HBC, and other aquatic organisms. The outputs of all these models were collected and used to calculate performance metrics under all the resource goals. The details of all these modeling methods are provided in the technical appendixes to the LTEMP EIS; a synopsis is provided here.

6.2 Hydrology

The hydrological modeling requires three sets of input: a time series of hydrological flow into Lake Powell, a time series of sediment input into the Colorado River from the Paria River and the Little Colorado River, and the operational rules determined by a long-term strategy. The output of the hydrological modeling is the monthly, daily, and hourly flows through Glen Canyon Dam for the 20-year LTEMP period of performance. This requires three modeling systems. First, the Colorado River Simulation System (CRSS), built with the commercial software package RiverWare™ (Zagona and others, 2001), generates monthly volumes and lake elevations taking into account the operations of the 12 primary reservoirs on the Colorado River. Second, the Generation and Transmission Maximization model (GTMax-Lite) generates daily and hourly flows taking into account patterns of demand and supply of electric power in the Colorado River Storage Project (CRSP) region. Third, a sand budget model tracks sediment in Glen, Marble, and Grand Canyons; and is used to indicate when sediment conditions warrant high-flow experiments (if the long-term strategy in question allows them). After the HFEs are identified, a second pass through GTMax-Lite is required to refine the daily and hourly flows. Note that the effect of TMFs on hydrology were not modelled because this would have required a full coupling of the hydrology and fish models (with feedback from the fish models to the hydrology models), which was a computing task that was beyond the resources available.

6.2.1 Critical Uncertainty

To model uncertainty in future inflow, the indexed sequential method (Ouarda and others, 1997) was used to resample the historical record of natural flow in the Colorado River system during the 105-year period from 1906 through 2010. Every fifth trace was selected from this series to produce 21 hydrological traces; every long-term strategy was evaluated against all 21 hydrological traces.

To investigate the possible effects of climate change on the performance of the long-term strategies, CRSS was run with 112 natural flow traces developed from downscaled general circulation model projected hydrological traces (Bureau of Reclamation, 2012). These climate scenarios were based on 16 general circulation models from the Coupled Model Intercomparison Project Phase 3 (CMIP3) using three forcing scenarios (A2, high; A1b, medium; and B1, low) (Maurer and others, 2007). The LTEMP models were not run with the 112 hydrological traces; rather, the 112 hydrological traces from the climate-change scenarios were used to place weights on the 21 index sequential historical traces. The model results are compared using historical (equal) and climate-change weights on the 21 hydrological traces.

6.3 Sediment Dynamics

A sand budget model (Russell and Huang, 2010; Wright and others, 2010) was used to track sand storage and transport from Lees Ferry (RM 0) to Bright Angel Creek (RM 87) (fig. 1). The sand budget model takes as input hourly hydrographs at the reach boundaries (RM 30, RM 61, and RM 87) developed based on release schedules from Glen Canyon Dam and hourly sand delivery from the Paria and Little Colorado Rivers. The model tracks sand storage and movement through three reaches (Upper Marble Canyon, RM 0 to 30; Lower Marble Canyon, RM 30 to 61; and Eastern Grand Canyon, RM 61 to 87) using empirically-based rating curves formulated on a particle-size-specific basis. The outputs of the model include hourly time series of the sand transported at the downstream border of each reach, and the sand budget for each reach. From these outputs a variety of performance metrics, including the SLI (performance metric 15), can be calculated.

6.3.1 Critical Uncertainty

Sediment input to the Colorado River between Lees Ferry and Bright Angel Creek comes primarily from the Paria River and the Little Colorado River (fig. 1). Variation in sediment input is driven by spatial and temporal variation in precipitation. To capture uncertainty about the time series of future sediment input, three 20-year traces of sediment input were created from historical records using an index sequential method. For Paria River input, 49 reconstructed historical traces were available (index years 1964–2012). For Little Colorado River input, 18 reconstructed historical traces were available (index years 1995–2012). The cumulative 20-year sediment delivery for each trace was calculated; and the traces corresponding to the 10th, 50th, and 90th quantiles of cumulative sediment delivery were selected to represent the range of possible uncertainty. The traces from corresponding quantiles for the Paria River and Little Colorado River delivery were coupled in the simulations. Weights were placed on the three sediment traces so that the weighted mean and standard deviation of the 20-year Paria River sediment delivery for the three traces matched the mean and standard deviation for the full set of index sequential Paria River traces.

6.4 Temperature

The average monthly water temperatures along the river corridor from Glen Canyon Dam to Lake Mead were forecast using the monthly flow and air temperatures forecasts. The release temperature from Glen Canyon Dam was simulated with the CE–QUAL–W2 model (Cole and Wells, 2006). This served as an input to a river temperature model that calculated the gains and losses of heat as the water moved downstream (Wright and others, 2009). For the purposes of the decision analysis, water temperature was an intermediate variable used as input to the fish models but not used directly as a performance metric.

6.5 Coupled Rainbow Trout-Humpback Chub Dynamics

A coupled RBT–HBC model was used to simulate the population dynamics of RBT in the Glen Canyon reach, movement of RBT from Lees Ferry to the Little Colorado River confluence, and the population dynamics of HBC in the Little Colorado River reach. The RBT population dynamics were simulated with an age-structured population model that accounted for the effects of water flow on recruitment, survival, growth, and downstream emigration (Korman and others, 2012). The RBT performance metrics are calculated from this model. The RBT catch rate (performance metric 3) was calculated from the age-specific abundances, age-specific vulnerabilities, and a catchability coefficient. The abundance of RBT greater than 16 inches (considered high-quality RBT; performance metric 5) was calculated from the age-specific abundances and size-at-age characteristics. The annual emigrants (performance metric 4) were computed as a fraction of the recruitment.

The RBT movement model predicts the monthly abundance of RBT in each 1-mile segment of the Colorado River from RM 0 to RM 150 taking into account movement rates, natural mortality, and implementation of mechanical removal. Movement and survival were density independent and were not affected by flow or temperature.

A size- and location-structured population model was used to predict the adult population size of HBC at monthly intervals (Yackulic and others, 2014). The HBC population size in two locations, the Colorado River and the Little Colorado River (a tributary of the Colorado River), was accounted for in the model. Survival of juvenile HBC in the Colorado River depended on the abundance of RBT in the Little Colorado River reach of the Colorado River; their growth depended on RBT abundance and temperature. Growth rates in other size classes in the Colorado River depended on water temperature. From this model, the minimum number of adult HBC during each 20-year trace was calculated, and the expected minimum value (performance metric 1) was calculated by taking the mean across traces.

6.5.1 Critical Uncertainties

A number of critical uncertainties concerned parameters in the RBT and HBC models. Each of these uncertainties was expressed as alternative sets of model parameters. All long-term strategies, with all sediment and hydrology traces, were run separately against the combinations of model parameters. The alternative sets of model parameters were assigned weights to represent their empirical support, and weighted averages of the performance metrics were calculated across them.

Uncertainty about the effect of fall HFEs on recruitment of RBT in the Glen Canyon reach was expressed as two hypotheses: one that there is no effect on recruitment, and another that proposed recruitment would increase at the same rate as seen with spring HFEs (Korman and others, 2011) but for only 1 year instead of 2 years. An expert panel consisting of four fish biologists who were familiar with RBT dynamics in the Colorado River was convened in March 2014. A modified Delphi process with four-point elicitation (Speirs-Bridge and others, 2010) was used to estimate the likelihood of the two hypotheses; the resulting individual estimates were aggregated by simple averaging.

Uncertainty about the effect of TMFs in reducing RBT recruitment in the Glen Canyon reach was expressed as two hypotheses by the expert panel: TMFs reduce recruitment by 10 percent, and TMFs reduce recruitment by 50 percent. The two levels of effectiveness were chosen to represent equally plausible extremes.

The final area of uncertainty concerned the effects of RBT abundance and temperature on the growth and survival of juvenile HBC in the Little Colorado River reach of the main stem Colorado River. Four hypotheses were generated (fig. 3*A* and 3*B*): a strong effect of temperature on growth and a strong effect of RBT on growth and survival (f1), a weak effect of temperature on growth and a weak effect of RBT on growth and survival (f2), a weak effect of temperature and a strong effect of RBT (g1), and a strong effect of temperature and a weak effect of RBT (g2). The parameter values for the four hypotheses were chosen from the ends of diameters on the 90-percent confidence ellipsoid for the joint parameter likelihood (Yackulic and others, 2014) and, thus, were equally weighted.

6.6 Fish Habitat Suitability

Temperature suitability for HBC and other native and nonnative fish at a number of sites between Lees Ferry (RM 0) and Diamond Creek (RM 225) (fig. 1) was evaluated with species-specific models for the effect of temperature on survival, reproduction, and growth (Valdez and Speas, 2007). The details of all these methods and results are in the LTEMP EIS.

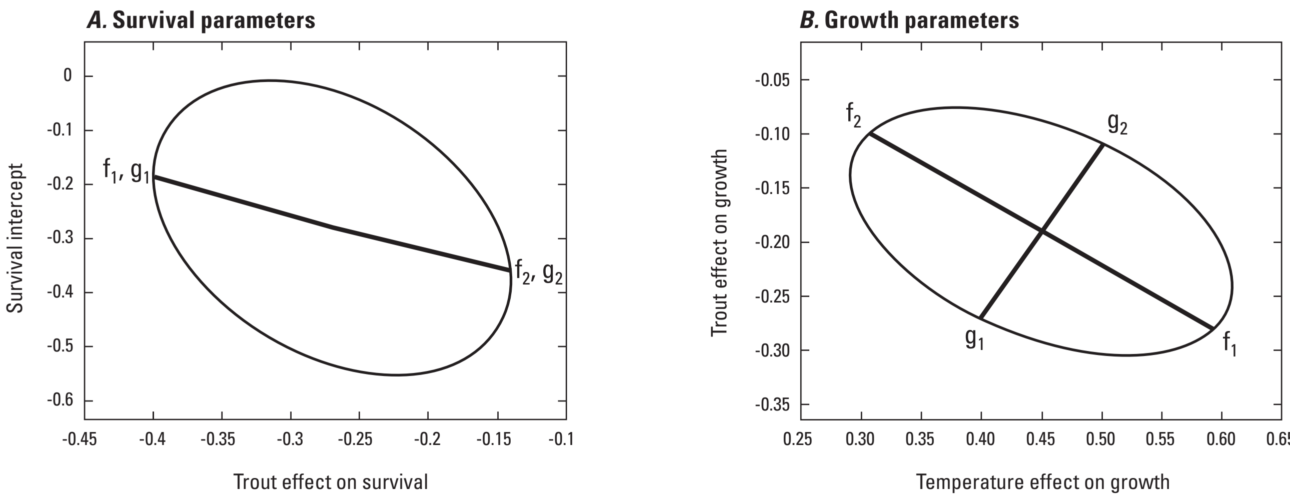

Figure 3. Uncertainty in the humpback chub population dynamics as represented by four alternative sets of parameters. *A*, survival parameters; and, *B*, growth parameters

The only one of those metrics that was retained for the decision analysis was the average temperature suitability for HBC at Havasu Creek (RM 157) and Pumpkin Spring (RM 213) because most of the other metrics exhibited very little difference across alternatives. Monthly water temperatures in the main stem Colorado River at the various sites under each long-term strategy were used to calculate the suitability for spawning, incubation, and growth during critical periods of the annual cycle. The overall temperature suitability at a site was the product of the suitability for the three component processes during the course of the year and could theoretically vary between 0 and 1 (performance metric 2).

6.7 Archaeological and Cultural Resources

The performance metrics associated with archaeological and cultural resources (performance metrics 6–8; table 1) did not require separate models but, rather, were calculated from intermediate sediment and flow variables.

6.8 Hydropower

As noted above in the “Hydrology” section (section 6.2), CRSS, the sand budget model, and GTMax-Lite are used in combination to simulate the water release and, therefore, hydropower generation on an hourly basis for each long-term strategy (fig. 2). The GTMax-Lite optimized the economic value of hourly energy produced at Glen Canyon Dam. This model determined an hour-by-hour pattern of generation (in megawatt hours) and water releases (in cubic feet per second) that satisfied the operating constraints imposed by each alternative, such as upramp and downramp rates, maximum change in the release during a rolling 24-hour period, maximum hourly release, and others. Hourly electricity market prices during the 20-year LTEMP period were determined using the AURORAxmp (Aurora) model to simulate the operation of the Western Interconnection of which Glen Canyon Dam is one of several thousand generating plants. Hourly prices determined by Aurora for 2013 were benchmarked against 2013 day-ahead market prices published by the Intercontinental Exchange. Prices forecast by Aurora for 2013 were compared against historical Intercontinental Exchange prices, and future electricity prices were adjusted accordingly.

For a given long-term strategy, the value of hydropower generation (performance metric 9) was calculated by combining the forecasts of the hourly generation profile and electricity market price. The net present value (NPV) of this 20-year time series was calculated assuming a 3.375 percent discount rate, and then divided by 20 to present the results on an annualized scale.

Hydropower capacity from Glen Canyon Dam is also marketed in the form of long-term firm contracts to provide power up to a given level. Energy demand is highest in August, so to calculate the marketable capacity (in megawatts), the peak daily generation was tabulated for each day in August across the 20 years of a trace (for each long-term strategy). From these 620 daily values (20 years x 31 days in August), the 90-percent exceedance value (10th quantile) was calculated, representing the marketable capacity for that trace. In 90 percent of August days (and much more often in other months), WAPA can be confident of being able to deliver that amount of power without having to purchase it. The net present value of that capacity (performance metric 10) was calculated by multiplying by the levelized cost of capacity plus fixed annual operating and maintenance (O&M) expenses of a thermal power plant constructed to replace capacity lost at Glen Canyon Dam. The selection of the replacement technology was based on insights obtained from the power systems economic analysis. The Aurora model runs made for this analysis determined that a natural gas combustion turbine would be the type of generating unit most likely constructed as a replacement for lost Glen Canyon Dam capacity. The cost to construct that type of unit, spread over its book life, was determined to be $50,100/MW-year, including capital investment costs, allowance for funds during construction, and fixed O&M costs. The source of cost data for replacement power plant capacity was U.S. Energy Information Administration (2014). In the analysis in the LTEMP EIS (chapter 4 and appendix K), the daily August generation values for all traces were combined before the exceedance value was calculated; this results in some slight differences in the median values presented but not systematic bias.

6.9 Recreation

The performance metrics associated with recreation (performance metrics 11–13; table 1) did not require separate models but, rather, were calculated from intermediate sediment and flow variables.

6.10 Riparian Vegetation

The effects of the long-term strategies on riparian vegetation were simulated with a state-and-transition model for Colorado River riparian vegetation downstream from Glen Canyon Dam (Ralston and others, 2014). The model tracks seven vegetation communities (bare sand, marsh, shrub wetland, tamarisk, cottonwood-willow, arrowweed, and mesquite) on channel margins and sandbars in the New High Water Zone and Fluctuation Zone as affected by the depth, timing, and duration of inundation. Six geomorphic submodels are included: lower separation bar, upper separation bar, lower reattachment bar, upper reattachment bar, lower channel margin, and upper channel margin; only four of these are unique (the parameters for the upper separation bar, upper reattachment bar, and upper channel margin are all equal). The model starts in 1 of 25 possible states (the 7 vegetation communities crossed with the 6 geomorphic submodels; not all of the 42 combinations are possible) and then tracks the vegetation state in each subsequent year as affected by the alternative-specific flows. The output is the number of years spent in each vegetation state during the 20-year LTEMP period of performance. These results are summed across the 25 starting states and then compared to the results that would have happened if the starting state was maintained for the 20-year period. In comparing the native to nonnative states, and in calculating the native diversity, the results are weighted by the current estimated area of each vegetation state.

Four component ratios are calculated as intermediate results: the ratio of cumulative to initial native vegetation cover, the ratio of cumulative to initial vegetation state diversity, the ratio of cumulative to initial native to nonnative dominant vegetation state, and the ratio of initial to cumulative cover of arrowweed. The final value (riparian native states and diversity index; performance metric 14) is the sum of the four component ratios; thus, an index value of 4.0 indicates an unchanged vegetation condition, values greater than 4.0 indicate improved vegetation conditions, and values less than 4.0 indicate degraded vegetation conditions.

7 Consequence Analysis Results

In this section, the results for the individual performance metrics are presented. In most cases, these results are reported as means over all sources of uncertainty with boxplots used to show the variance induced by uncertainty. Unless otherwise noted, the historical weighting of hydrological traces was used; the sensitivity of the results to climate change (as captured by weighting of the hydrological traces) is discussed in section 8.4, “Effects of Climate Change.”

7.1 Humpback Chub Results

Across alternatives, the expected (mean) minimum number of adult HBC during the 20-year LTEMP period of performance differed by about 500 from Alternative A (fig. 4, bottom panel). The variation across hydrological traces within an alternative was greater than the magnitude of variation across alternatives. Many of the long-term strategies were demonstrably better than Alternative A; the biggest exceptions (C2 and F) were long-term strategies that increased RBT recruitment (through HFEs) without tools to manage RBT populations (TMFs and mechanical removal). The best-performing long-term strategy (E6) did not allow HFEs of any type and included triggered use of TMFs if needed. The benefit of low summer flows to HBC (compare D1 to D4) is not discernible, likely because of their infrequent use.

The set of 16 scenarios that captured critical uncertainty did not affect the dominance of long-term strategy E6 (table 4); that is, if the only desired outcome is to maximize the HBC metric, the best long-term strategy is E6 regardless of the effect of fall HFEs or TMFs on RBT recruitment or the relative effects of temperature and RBT on juvenile HBC growth and survival. For the purpose of the HBC objective, therefore, the expected value of information across the critical uncertainties that were articulated is 0.

Across the uncertainty represented by the hydrological traces, there is a small value of information (table 5). For most hydrological traces, the best long-term strategy for HBC was E6; but long-term strategies B2, C3, D1, and E5 were also favored in some traces. In the face of uncertainty, the best strategy is E6 with an expected (mean) minimum adult population size of 5,708. If the hydrological trace could be known in advance of choosing an action, the appropriate strategy (B2, C3, D1, E5, or E6) would be chosen; the expected minimum adult population size would be 5,725, which is an increase of 0.30 percent. Of course, the hydrological trace cannot be known in advance of choosing an action because it represents environmental variation during the next 20 years, but the inclusion of these results is helpful in understanding the value

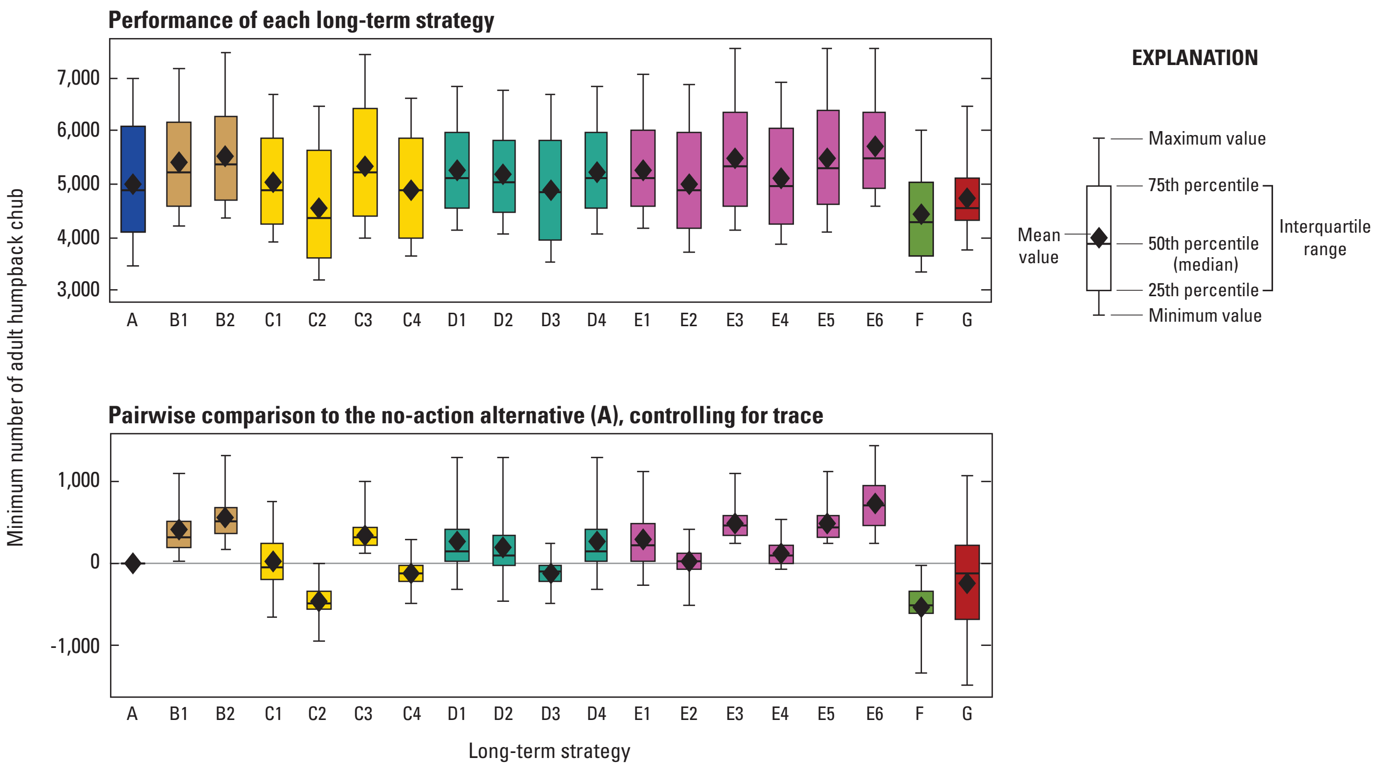

Figure 4. Minimum number of adult humpback chub (performance metric 1) forecast for 19 long-term strategies with equal weighting of traces.

of information for resolvable uncertainty (the 16 scenarios) relative to the value of information for background environmental variation.

The value of information depends on the set of long-term strategies evaluated. The calculations just described assume the decision maker is choosing from the entire set of 19 long-term strategies. In practice, it is more likely that one of the alternatives would be chosen, and the long-term strategy would be chosen from within the set associated with that alternative. The value of information in resolving the critical uncertainties is 0 for all alternatives except Alternative C, which has a value of information of 8.5 adult HBC (table 6).

Temperature suitability for HBC was forecast at a number of locations in the main stem Colorado River, and in most cases the suitability was low (less than 0.03 on a scale of 0 to 1). At the two locations farthest downstream (Havasu Creek, RM 157; Pumpkin Spring, RM 213; fig. 1), the average suitability was around 0.1 (on a scale of 0 to 1). The temperature suitability for HBC was affected more by hydrology than by the long-term strategy; only Alternative F stood out from the other alternatives (fig. 5). Alternative G, with its year-round steady flows, provided the best suitability (mean 0.102); its ranking above the other long-term strategies was not affected by any of the critical uncertainties (table 6). There was a small effect of the hydrological trace on the ranking of alternatives based on temperature suitability (EVXI; 0.77 percent; table 6).

7.2 Rainbow Trout Fishery Results

The RBT performance metrics differed substantially across long-term strategies (figs. 6–8). The RBT catch rate (performance metric 3) and RBT emigration rate (performance metric 4) were highly correlated with one another because both were driven by the RBT population size. Catch rate and emigration rate were highest for those long-term strategies that implemented many HFEs but did not allow TMFs (C2, C4, D3, E2, and F) or that provided steady flows that supported RBT recruitment (G) (figs. 6–7). The abundance of high-quality RBT (greater than 16 inches in length, performance metric 5) was negatively correlated with RBT population size; the best long-term strategies were those that restricted or did not allow HFEs (B1, B2, C3, E3, E5, E6) (fig. 8).

Apart from the HBC metric when only the strategies under Alternative C were considered, the RBT performance metrics were the only ones affected by the critical uncertainties; the fall HFE hypothesis had an EVXI of 0.26 percent, 3.50 percent, and 0.98 percent for the three performance metrics, respectively (table 6). Across all performance metrics and all uncertainties, the strongest effect was the effect of the combined hydrological/sediment trace on the RBT catch rate with an EVXI of 7.53 percent (table 6). The uncertainty about the effectiveness of TMFs did not affect the top ranked long-term strategy for any of the trout or other performance metrics (table 6).

Table 4. Effect of critical uncertainty on minimum adult humpback chub population size (performance metric 1).

[The cell entries show the expected minimum humpback chub population size for each long-term strategy in each combination of hypotheses. The hypotheses are if high-flow experiments increase rainbow trout recruitment (N, no; Y, yes), how effective rainbow trout management flows are (H, high effectiveness; L, low effectiveness), and the relative effects of temperature and rainbow trout on juvenile humpback chub survival and growth (f1, f2, g1, and g2). A solid dot (●) indicates the result is averaged over this uncertainty. The highlighted long-term strategy is the best performing alternative in each row. HFE, high-flow experiments; TMF, trout management flow; RBT, rainbow trout]

Fall HFE	TMF	Model	A	B1	B2	C1	C2	C3	C4	D1	D2	D3	D4	E1	E2	E3	E4	E5	E6	F	G
N	H	f1	5,204	5,712	5,858	5,463	4,766	5,408	5,402	5,655	5,576	5,174	5,645	5,839	5,500	5,580	5,574	5,572	5,900	4,409	5,082
N	H	f2	5,116	5,413	5,520	5,268	4,772	5,253	5,246	5,324	5,275	5,050	5,318	5,482	5,298	5,357	5,352	5,351	5,521	4,545	5,028
N	H	g1	5,195	5,774	5,941	5,430	4,632	5,377	5,372	5,655	5,556	5,116	5,646	5,874	5,500	5,597	5,593	5,582	5,947	4,184	5,042
N	H	g2	5,135	5,396	5,486	5,324	4,901	5,303	5,295	5,368	5,329	5,125	5,359	5,493	5,327	5,375	5,369	5,376	5,527	4,773	5,078
N	L	f1	5,204	5,653	5,799	5,251	4,766	5,408	5,402	5,439	5,367	5,003	5,432	5,790	5,500	5,580	5,574	5,572	5,857	4,409	4,803
N	L	f2	5,116	5,382	5,487	5,132	4,772	5,253	5,246	5,214	5,168	4,959	5,209	5,457	5,298	5,357	5,352	5,351	5,500	4,545	4,855
N	L	g1	5,195	5,710	5,877	5,189	4,632	5,377	5,372	5,420	5,332	4,931	5,415	5,822	5,500	5,597	5,593	5,582	5,902	4,184	4,739
N	L	g2	5,135	5,367	5,457	5,206	4,901	5,303	5,295	5,265	5,228	5,036	5,257	5,470	5,327	5,375	5,369	5,376	5,507	4,773	4,922
Y	H	f1	4,803	5,340	5,538	4,824	4,210	5,408	4,365	5,266	5,179	4,781	5,258	4,936	4,608	5,580	4,727	5,572	5,900	4,352	4,603
Y	H	f2	4,870	5,193	5,327	4,878	4,412	5,253	4,559	5,104	5,051	4,820	5,100	4,948	4,715	5,357	4,808	5,351	5,521	4,494	4,709
Y	H	g1	4,748	5,349	5,578	4,720	4,038	5,377	4,232	5,214	5,111	4,680	5,208	4,861	4,496	5,597	4,643	5,582	5,947	4,126	4,549
Y	H	g2	4,916	5,201	5,317	4,974	4,571	5,303	4,679	5,168	5,124	4,914	5,161	5,019	4,814	5,375	4,886	5,376	5,527	4,726	4,762
Y	L	f1	4,803	5,280	5,475	4,639	4,210	5,408	4,365	5,015	4,939	4,575	5,010	4,880	4,608	5,580	4,727	5,572	5,857	4,352	4,364
Y	L	f2	4,870	5,159	5,291	4,755	4,412	5,253	4,559	4,972	4,924	4,702	4,969	4,913	4,715	5,357	4,808	5,351	5,500	4,494	4,557
Y	L	g1	4,748	5,282	5,509	4,521	4,038	5,377	4,232	4,950	4,860	4,472	4,947	4,801	4,496	5,597	4,643	5,582	5,902	4,126	4,292
Y	L	g2	4,916	5,170	5,285	4,864	4,571	5,303	4,679	5,042	5,001	4,793	5,036	4,988	4,814	5,375	4,886	5,376	5,507	4,726	4,621
Grand mean																					
●	●	●	4,991	5,392	5,541	5,016	4,527	5,335	4,874	5,247	5,181	4,876	5,241	5,269	5,015	5,477	5,103	5,470	5,708	4,450	4,741
Effect of fall HFE hypotheses																					
N	●	●	5,162	5,551	5,678	5,283	4,768	5,335	5,328	5,417	5,354	5,049	5,410	5,653	5,406	5,477	5,472	5,470	5,708	4,478	4,943
Y	●	●	4,835	5,247	5,415	4,772	4,308	5,335	4,459	5,091	5,024	4,717	5,086	4,918	4,658	5,477	4,766	5,470	5,708	4,424	4,557
Effect of TMF hypotheses																					
●	H	●	4,991	5,415	5,565	5,098	4,527	5,335	4,874	5,337	5,268	4,950	5,330	5,290	5,015	5,477	5,103	5,470	5,724	4,450	4,847
●	L	●	4,991	5,368	5,516	4,933	4,527	5,335	4,874	5,157	5,094	4,801	5,152	5,248	5,015	5,477	5,103	5,470	5,691	4,450	4,636
Effect of temperature and RBT hypotheses																					
●	●	f1	4,995	5,488	5,660	5,030	4,475	5,408	4,859	5,334	5,256	4,874	5,327	5,340	5,034	5,580	5,131	5,572	5,878	4,379	4,702
●	●	f2	4,987	5,281	5,402	5,000	4,584	5,253	4,887	5,148	5,099	4,877	5,144	5,188	4,993	5,357	5,067	5,351	5,510	4,518	4,780
●	●	g1	4,961	5,519	5,718	4,949	4,322	5,377	4,776	5,299	5,204	4,789	5,293	5,316	4,975	5,597	5,096	5,582	5,925	4,154	4,645
●	●	g2	5,021	5,279	5,382	5,084	4,728	5,303	4,972	5,206	5,166	4,962	5,199	5,232	5,059	5,375	5,117	5,376	5,517	4,748	4,839

Table 5. Effect of hydrological trace on minimum adult humpback chub population size (performance metric 1).

[The cell entries show the expected minimum adult humpback chub population size for each long-term strategy, under each hydrological trace, averaged over the sediment traces and critical uncertainties. The bottom row shows the mean over the hydrological traces. The highlighted long-term strategy is the best performing alternative in each row. The best strategy in the face of uncertainty has an expected minimum population size of 5,708; the expected minimum population size if the hydrological trace could be known before the strategy was selected is 5,725 (average of the highlighted cells). Thus, the expected value of information, for resolving uncertainty about the future hydrology, is an increase of 17 adults in the minimum humpback chub population.]

Trace	A	B1	B2	C1	C2	C3	C4	D1	D2	D3	D4	E1	E2	E3	E4	E5	E6	F	G
h00	3,680	4,570	4,575	4,258	3,286	4,113	3,772	4,616	4,574	3,732	4,617	4,615	3,875	4,252	3,986	4,182	4,887	3,419	4,326
h01	3,789	4,804	4,812	4,279	3,284	4,050	3,670	4,692	4,613	3,740	4,692	4,708	3,779	4,182	3,892	4,136	5,038	3,357	4,519
h02	3,742	4,403	4,406	3,991	3,304	3,964	3,656	4,372	4,325	3,609	4,370	4,344	3,820	4,131	3,936	4,085	4,592	3,391	4,155
h03	4,035	4,325	4,434	4,007	3,476	4,307	3,959	4,306	4,206	3,909	4,287	4,402	4,197	4,576	4,266	4,610	4,837	3,493	4,208
h04	5,047	5,443	5,591	4978	4,401	5,345	4,892	5,083	5,026	4,930	5,071	5,147	4,944	5,455	5,076	5,450	5,639	4,430	4,674
h05	6,386	6,619	6,901	6,166	5,940	6,873	6,164	6,234	6,152	6,126	6,236	6,318	6,335	6,998	6,433	7,008	6,998	5,767	5,226
h06	4,200	4,497	4,794	4,048	3,726	4,563	4,102	4,324	4,258	4,097	4,292	4,242	4,240	4,735	4,330	4,739	4,735	3,664	3,918
h07	4,206	4,386	4,555	4,274	3,972	4,618	4,207	4,445	4,347	4,245	4,445	4,535	4,448	4,857	4,518	4,857	4,918	3,765	4,421
h08	5,176	5,303	5,378	4,988	4,733	5,364	5,064	5,317	5,278	5,165	5,323	5,262	5,274	5,523	5,304	5,543	5,523	4,364	4,831
h09	5,435	5,561	5,726	5,297	5,193	5,580	5,269	5,746	5,704	5,528	5,730	5,486	5,414	5,714	5,453	5,703	5,713	4,864	4,953
h10	6,053	6,160	6,258	6,036	5,913	6,413	6,049	6,035	5,970	5,900	6,030	5,984	5,976	6,362	6,048	6,377	6,362	5,792	5,433
h11	6,788	7,118	7,349	6,630	6,365	7,433	6,577	6,710	6,646	6,551	6,735	6,792	6,802	7,544	6,867	7,553	7,544	6,003	5,526
h12	6,310	6,560	6,677	5,854	5,580	6,628	5,879	6,048	5,930	5,906	6,040	6,242	6,200	6,967	6,314	6,998	6,970	5,035	5,052
h13	4,511	4,965	5,111	4,567	4,005	4,868	4,372	4,657	4,614	4,350	4,673	4,791	4,565	5,080	4,643	5,071	5,340	4,026	4,107
h14	4,120	5,185	5,313	4,644	3,663	4,391	4,045	5,029	4,986	3,931	4,991	4,828	4,151	4,513	4,236	4,479	5,166	3,713	4,436
h15	4,130	4,543	4,715	4,097	3,601	4,368	3,981	4,256	4,160	4,024	4,186	4,342	4,011	4,458	4,124	4,442	4,745	3,668	4,202
h16	5,013	5,313	5,674	5,172	4,716	5,772	5,186	5,229	5,159	4,966	5,218	5,292	5,135	5,682	5,201	5,679	5838	4,761	4,568
h17	4,994	5,213	5,375	4,948	4,615	5,210	4,942	5,347	5,281	5,079	5,347	5,221	5,036	5,317	5,099	5,309	5,471	4,638	4,938
h18	6,419	6,586	6,692	6,192	5,814	6,653	6,201	6,476	6,432	6,328	6,489	6,503	6,457	6,803	6,505	6,818	6,857	5,905	6,009
h19	6,678	7,055	7,339	6,506	5,895	7,076	6,354	6,540	6,468	6,242	6,555	6,880	6,511	7,210	6,674	7,202	7,570	5,832	5,801
h20	4,098	4,617	4,678	4,395	3,590	4,450	4,004	4,721	4,675	4,027	4,725	4,710	4,150	4,659	4,254	4,629	5,117	3,559	4,267
Mean	**4,991**	**5,392**	**5,541**	**5,016**	**4,527**	**5,335**	**4,874**	**5,247**	**5,181**	**4,876**	**5,241**	**5,269**	**5,015**	**5,477**	**5,103**	**5,470**	**5,708**	**4,450**	**4,741**

Table 6. Expected value of information, by performance metric, for resolving critical uncertainty.

[See table 1 for a list of performance metrics. The best performance is the expected value of the performance metric across all uncertainties for the long-term strategy that maximized or minimized the performance metric. The value of perfectly resolving uncertainty across the 16 formal hypotheses about critical parameters is shown when all 19 long-term strategies are considered; only the two long-term strategies of alternative B are considered; and only the four, four, or six long-term strategies of alternatives C, D, and E are considered, respectively. Partial values of information are shown for resolving only the uncertainty about the effects of fall high-flow experiments on rainbow trout recruitment, efficacy of trout management flows, and effects of temperature and rainbow trout on humpback chub. Finally, the partial values of information are shown for resolving uncertainty about the combined hydrological-sediment trace, just the sediment trace, and just the hydrological trace. For the performance metrics not shown, all values of information were 0. min, minimum; HBC, humpback chub; TempSuit, temperature suitability index; Qual, quality; RBT, rainbow trout; WTSI, wind transport of sediment index; GC flow, Glen Canyon flow index; TOR, time-off-river index; CAI, camping area index; Veg, riparian vegetation index; SLI, sand load index; max, maximum; EVPI, expected value of perfect information; EVXI, expected value of partial information; HFE, high-flow experiment; TMF, trout management flow; ~, value less than 0.01 percent]

Performance metric	1	2	3	4	5	6	7	8	9	11	14	15	16
	minHBC	TempSuit	RBT Catch	Emigrate	Qual RBT	WTSI	GC flow	TOR	Power	CAI	Veg	SLI	Marsh
Desired direction	max	max	max	min	max	max	min	max	max	max	max	max	max
Best performance	5,708	0.102	3.367	22,415	956	0.465	18.4	0.840	150.41	0.451	3.954	0.576	1.101
Best action	E6	G	F	E6	E6	G	E3	G	B2	G	D4	G	E6
EVPI (16, all)	0.0	0.000	0.009	785	9.3	0.000	0.0	0.000	0.00	0.000	0.000	0.000	0.000
EVPI (16, B)	0.0	0.000	0.000	0	0.0	0.000	0.0	0.000	0.00	0.000	0.000	0.000	0.000
EVPI (16, C)	8.5	0.000	0.000	237	0.8	0.000	0.0	0.000	0.00	0.000	0.000	0.000	0.000
EVPI (16, D)	0.0	0.000	0.000	0	0.0	0.000	0.0	0.000	0.00	0.000	0.000	0.000	0.000
EVPI (16, E)	0.0	0.000	0.000	0	0.0	0.000	0.0	0.000	0.00	0.000	0.000	0.000	0.000
EVXI (fall HFE)	0.0	0.000	0.009	785	9.3	0.000	0.0	0.000	0.00	0.000	0.000	0.000	0.000
EVXI (TMF)	0.0	0.000	0.000	0	0.0	0.000	0.0	0.000	0.00	0.000	0.000	0.000	0.000
EVXI (HBC)	0.0	0.000	0.000	0	0.0	0.000	0.0	0.000	0.00	0.000	0.000	0.000	0.000
EVXI (traces)	19.0	0.001	0.254	1,033	8.4	0.003	0.9	0.001	0.35	0.007	0.224	0.021	0.035
EVXI (sediment)	0.0	0.000	0.000	37	0.0	0.000	0.0	0.000	0.00	0.000	0.012	0.000	0.000
EVXI (hydrology)	17.0	0.001	0.198	636	5.5	0.002	0.9	0.001	0.35	0.004	0.212	0.015	0.032
As a percent of the best performance													
EVPI (16, all), in percent	~	~	0.26	3.50	0.98	~	~	~	~	~	~	~	~
EVPI (16, B)	~	~	~	~	~	~	~	~	~	~	~	~	~
EVPI (16, C), in percent	0.15	~	~	1.06	0.09	~	~	~	~	~	~	~	~
EVPI (16, D)	~	~	~	~	~	~	~	~	~	~	~	~	~
EVPI (16, E)	~	~	~	~	~	~	~	~	~	~	~	~	~
EVXI (fall HFE), in percent	~	~	0.26	3.50	0.98	~	~	~	~	~	~	~	~
EVXI (TMF)	~	~	~	~	~	~	~	~	~	~	~	~	~
EVXI (chub)	~	~	~	~	~	~	~	~	~	~	~	~	~
EVXI (traces), in percent	0.33	1.39	7.53	4.61	0.88	0.59	4.78	0.10	0.23	1.63	5.66	3.57	3.20
EVXI (sediment), in percent	~	~	~	0.17	~	~	~	0.03	~	~	0.30	~	~
EVXI (hydrology), in percent	0.30	0.77	5.89	2.84	0.58	0.44	4.77	0.08	0.23	0.96	5.36	2.58	2.91

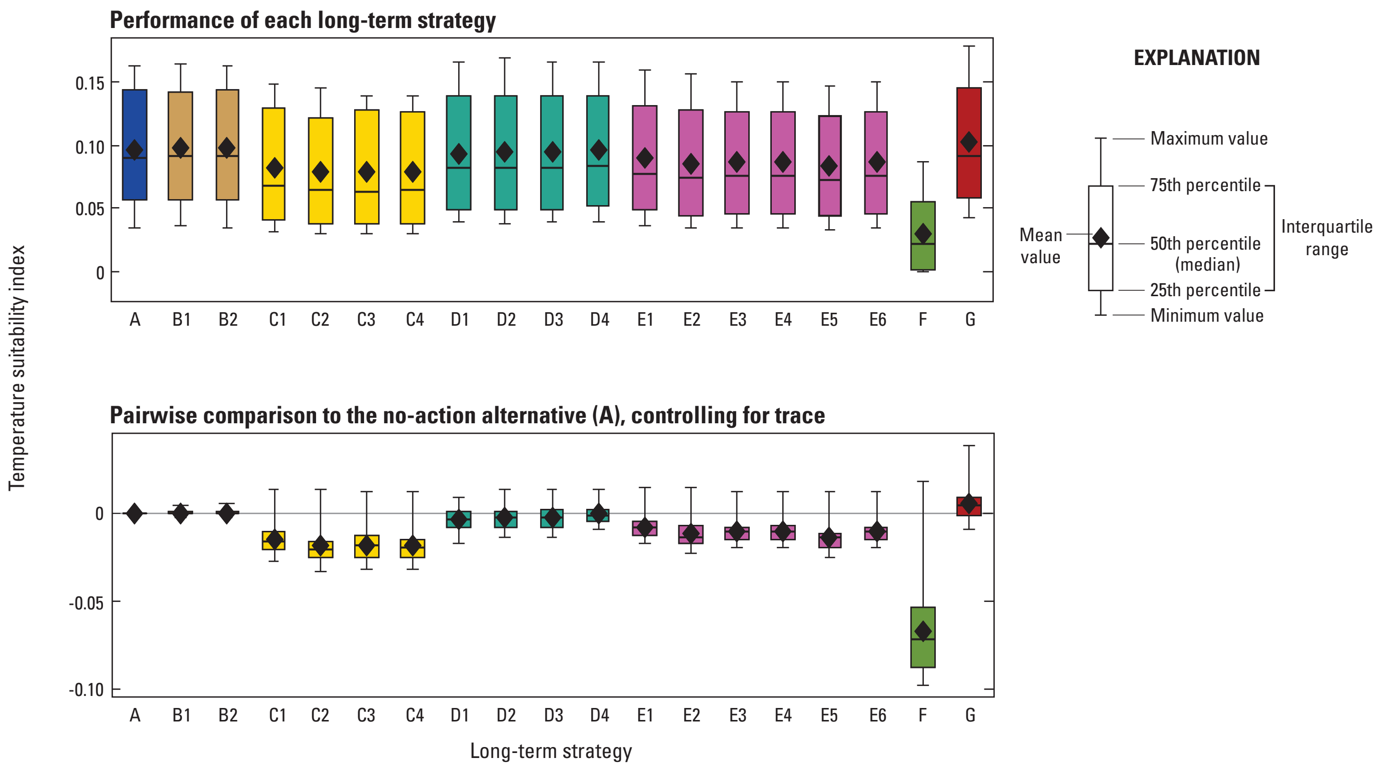

Figure 5. Temperature suitability index for humpback chub at river mile 157 and 213 (performance metric 2) forecast for 19 long-term strategies with equal weighting of traces.

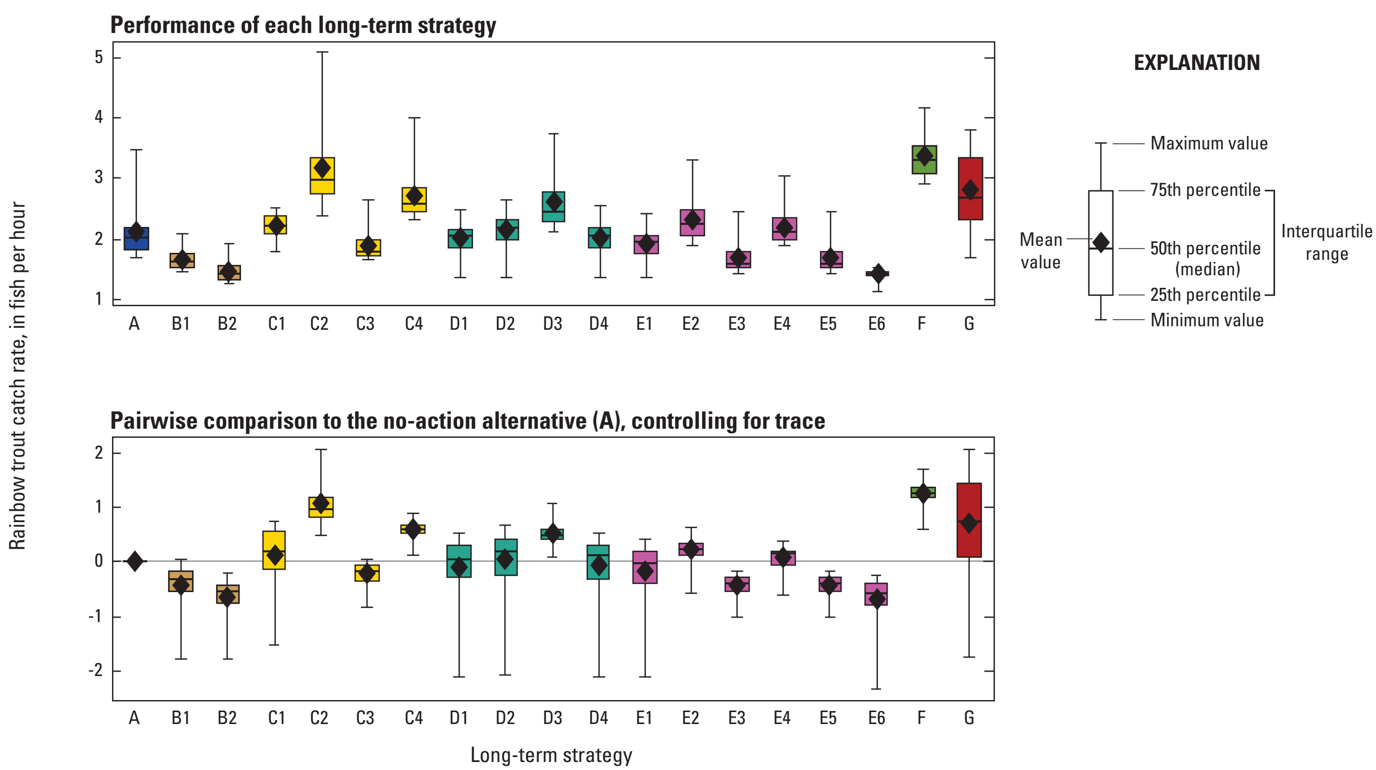

Figure 6. Rainbow trout catch rate (performance metric 3) forecast for 19 long-term strategies with equal weighting of traces.

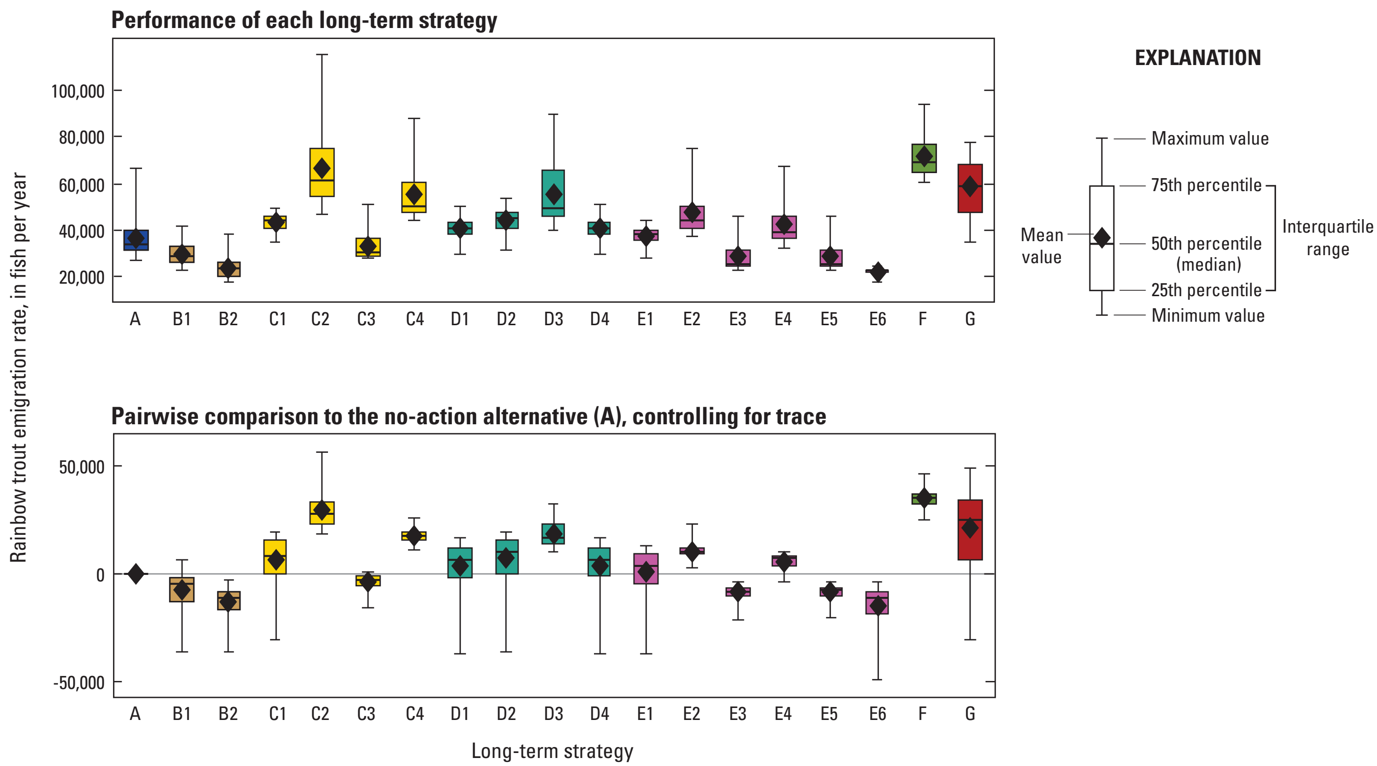

Figure 7. Rainbow trout emigration rate from Glen Canyon (performance metric 4) forecast for 19 long-term strategies with equal weighting of traces.

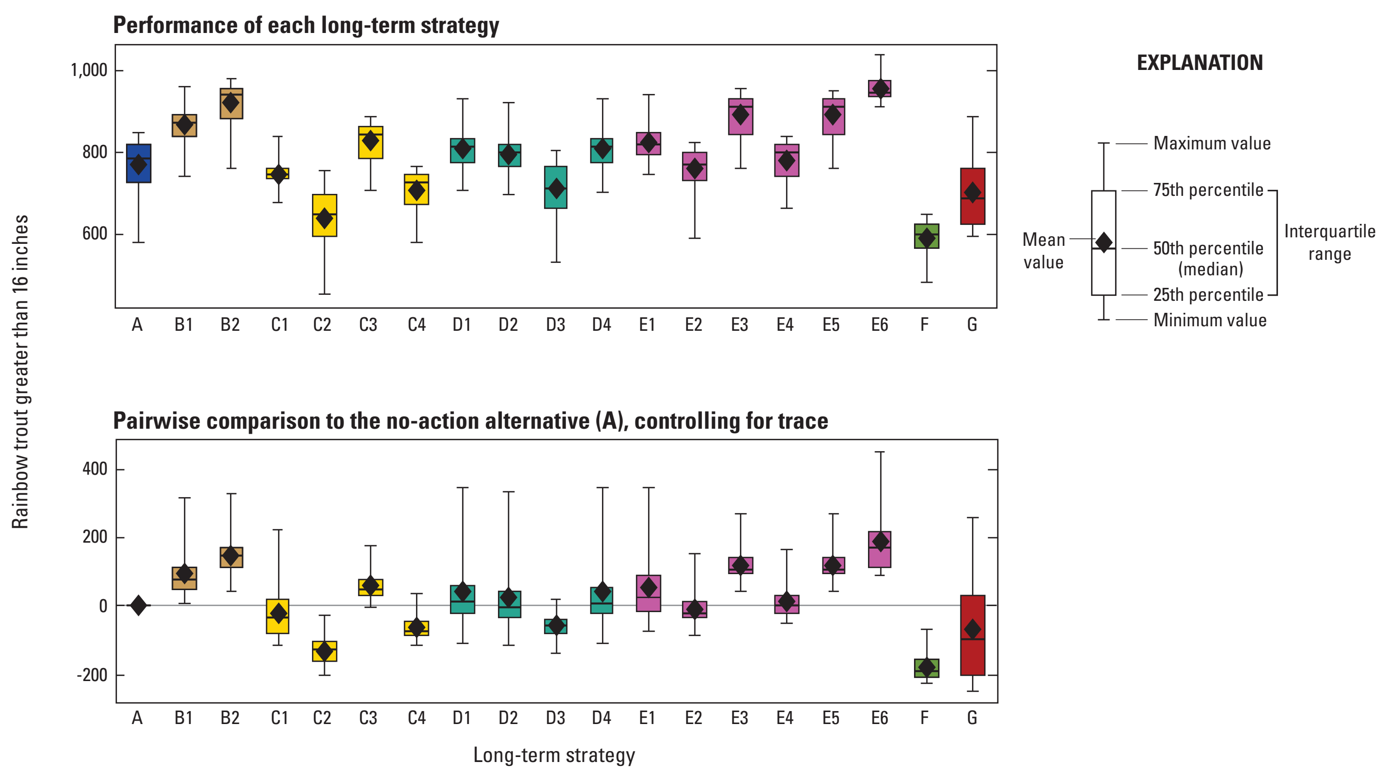

Figure 8. Abundance of high-quality rainbow trout (performance metric 5) forecast for 19 long-term strategies with equal weighting of traces.

7.3 Archeological and Cultural Resources Results

The protection of archeological and cultural resources was reflected in three performance metrics. The WTSI (performance metric 6) was largely driven by the SLI (performance metric 15) and was highest for those long-term strategies that implemented HFEs often (fig. 9). The best-performing alternative for WTSI was Alternative G (mean WTSI, 0.465); this ranking was not affected by any of the critical uncertainties or uncertainty in the sediment input (table 6). For some hydrological traces, long-term strategy C1 outperformed G, but the value of information related to hydrological uncertainty was small (0.44 percent).

The Glen Canyon flow index (performance metric 7) differed little among alternatives with a mean of around 20 days per year in which the flow exceeded 23,200 ft^3/s (fig. 10). Only Alternative F differed from the other long-term strategies (mean 36.8 days/year). The long-term strategies that did not allow HFEs (C3, E3, E5, and E6) had the best performance (smallest Glen Canyon flow index). The top ranking long-term strategy was not affected by critical uncertainty or sediment trace (table 6) but did vary depending on the hydrological trace (EVXI, 4.77 percent).

The time-off-river index (performance metric 8) was affected most strongly by the hydrological trace but was also weakly affected by the long-term strategy (fig. 11). Alternatives B and C were indistinguishable from Alternative A; Alternatives D, E, and G performed slightly better than Alternative A; and Alternative F performed noticeably worse because high flows during the peak rafting season allow quicker trips and more discretionary time at camping stops. Long-term strategies E1 and G were the best-performing strategies across hydrological and sediment traces, with only a small value of information associated with the trace uncertainty and no value of information associated with the critical uncertainties (table 6).

7.4 Hydropower Generation and Capacity Results

The best-performing long-term strategy for hydropower generation (performance metric 9) was B2, a long-term strategy designed to match power generation more closely to demand (fig. 12). For most of the long-term strategies, the annual value of hydropower generation is within \$3 million of the value from Alternative A, except for Alternatives F and G for which annual generation is \$6 million to \$8 million less than Alternative A (fig. 12). The effect of hydrology on hydropower generation is much greater than the effect of the alternatives, with the average annual power generation over 20 years varying more than \$60 million across hydrological traces (fig. 12). The dominance of B2 as the best long-term strategy for hydropower generation, however, is robust to uncertainty in hydrology with a value of information of only \$350,000 per year (EVXI, 0.23 percent, table 6); for 4 out of 21 hydrological traces, long-term strategy E3 outranked B2.

The value of hydropower capacity (performance metric 10) was more sensitive to the choice of long-term strategy than hydropower generation with long-term strategies differing by nearly \$20 million per year (fig. 13). Long-term strategy B2 was the best-performing strategy across all uncertainties, including hydrological trace. The long-term strategies in Alternative B outperformed Alternative A; all the remaining long-term strategies had a lower value of hydropower capacity than Alternative A (fig. 13). The value of capacity was somewhat sensitive to hydrological trace (the range of performance within a long-term strategy varied by \$8 million to \$17 million per year across hydrological traces), but the identification of the best-performing alternative was not (EVXI, 0).

7.5 Recreational Experience Results

The camping area index (performance metric 11), a metric composed from the SLI to represent beach formation and a flow factor to represent beach exposure, was highly correlated with the SLI (performance metric 18). The best-performing long-term strategies (especially C1, F, and G) include frequent implementation of HFEs; the worst-performing long-term strategies (for example, C3, E3, E5, and E6) do not permit HFEs (fig. 14). The identification of the top-ranked long-term strategy was affected by the combination of hydrological and sediment trace (EVXI, 1.96 percent) but not by any other uncertainties (table 6).

The fluctuation index (performance metric 12), which reflects the fraction of time the daily flow fluctuations are in a tolerable range for recreation, was highest for Alternatives F and G and lowest for Alternative B (fig. 15). Alternative D was comparable to Alternative A. The effect of the long-term strategies within an alternative was small compared to the effect of the base operations within each alternative. The fluctuation index was not strongly affected by any of the uncertainties, including hydrological trace.

The Glen Canyon rafting use metric (performance metric 13), which reflects the visitor-days lost per year because of HFEs, was best for those long-term strategies that did not permit HFEs (for example, C3, E3, E5, and E6) and worst for Alternative F (fig. 16). Under Alternative F, nearly 1,000 boat seats per year in Glen Canyon are expected to be lost because of HFEs. The rafting use metric showed variation as a result of hydrological trace, but the identification of the best-performing long-term strategies was not affected by any of the uncertainties.

7.6 Riparian Vegetation Results

The riparian vegetation index (performance metric 14) was the sum of four ratios that represented measures of different aspects of the vegetation community with a score of 4 indicating maintenance of current conditions.

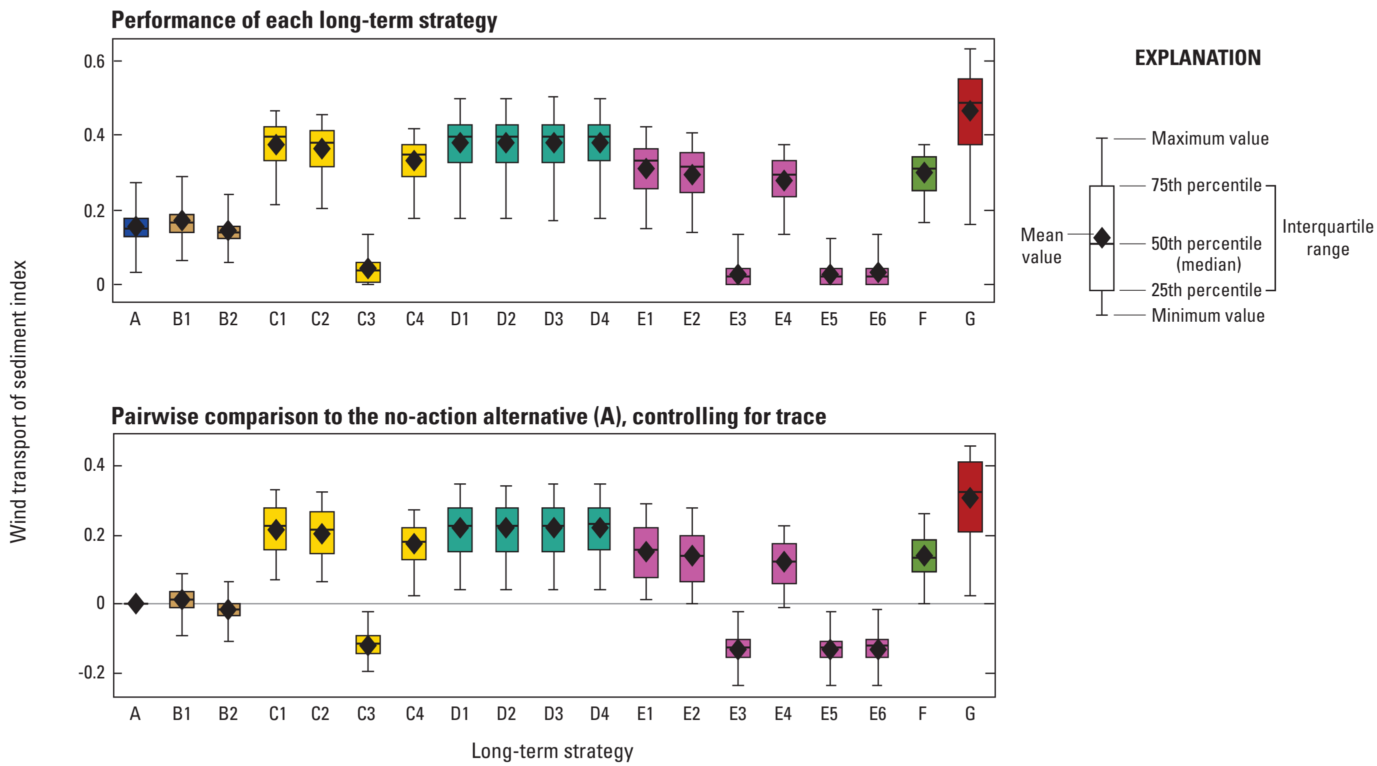

Figure 9. Wind transport of sediment index (performance metric 6) forecast for 19 long-term strategies with equal weighting of traces.

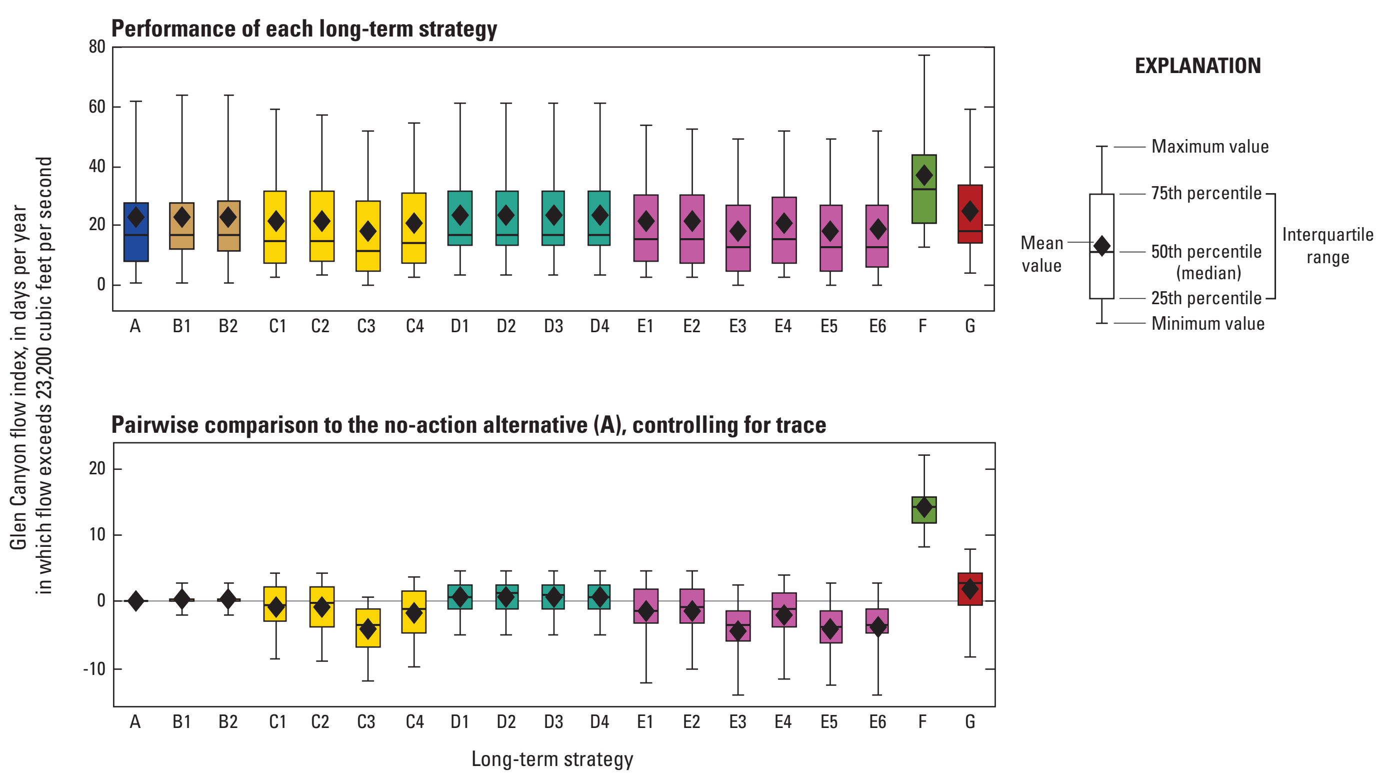

Figure 10. Glen Canyon flow index (performance metric 7) forecast for 19 long-term strategies with equal weighting of traces.

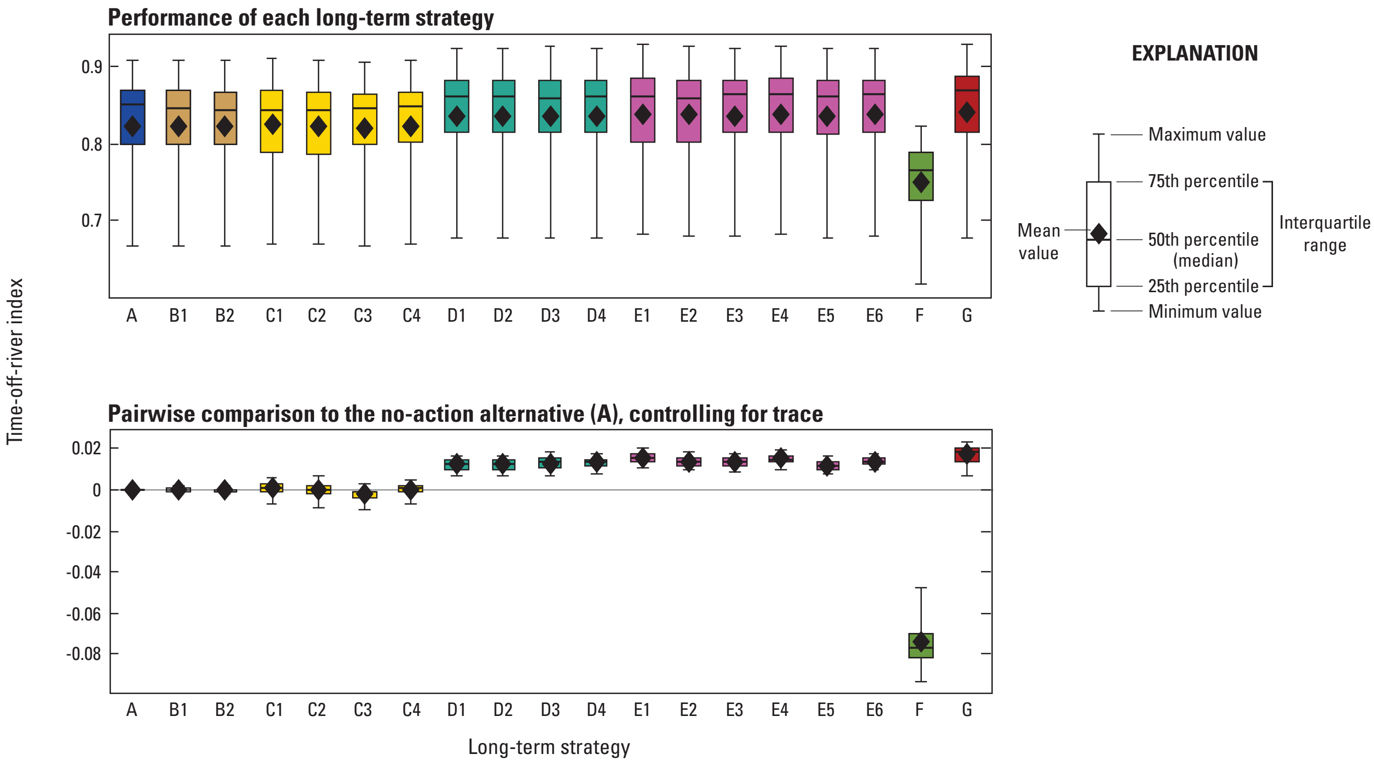

Figure 11. Cultural resources time-off-river index (performance metric 8) forecast for 19 long-term strategies with equal weighting of traces.

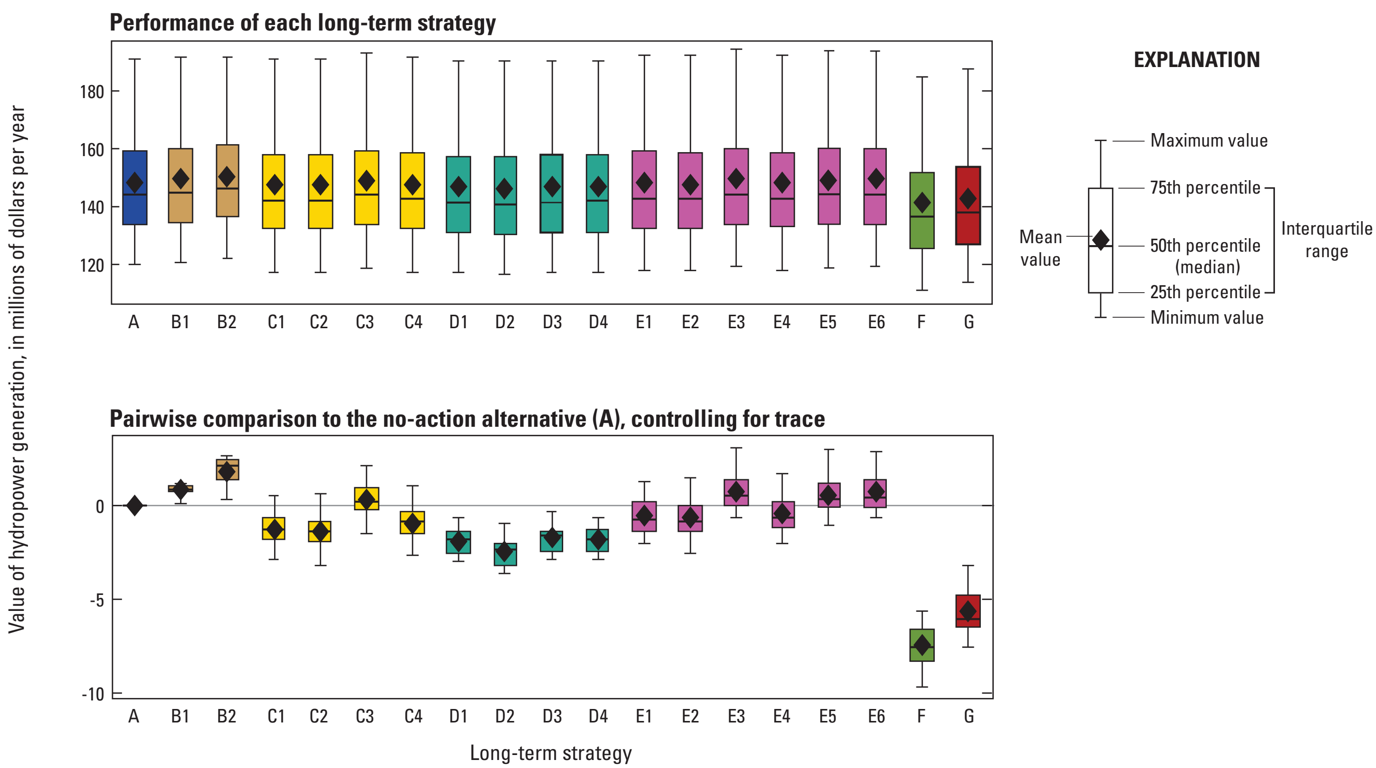

Figure 12. Annualized net present value of hydropower generation (performance metric 9) forecast for 19 long-term strategies with equal weighting of traces.

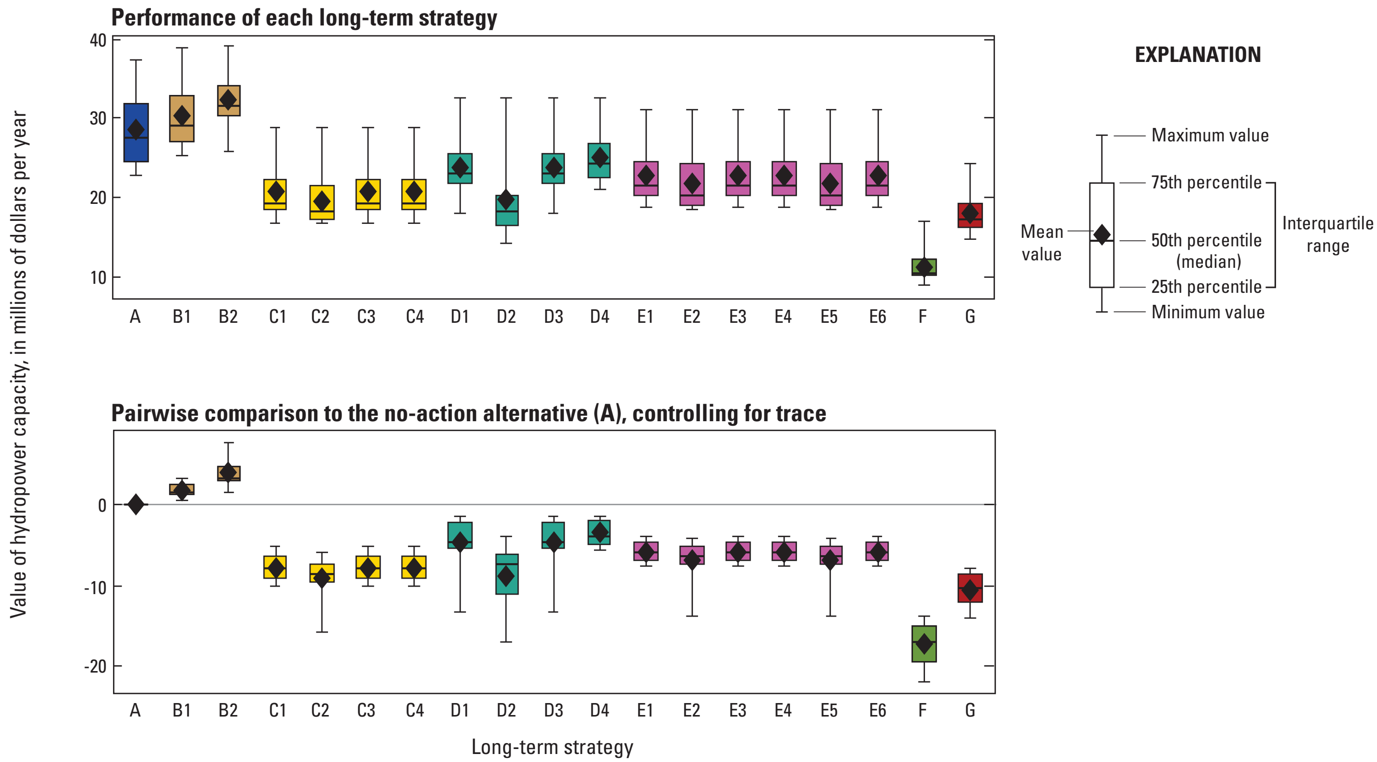

Figure 13. Annualized net present value of hydropower capacity (performance metric 10) forecast for 19 long-term strategies with equal weighting of traces.

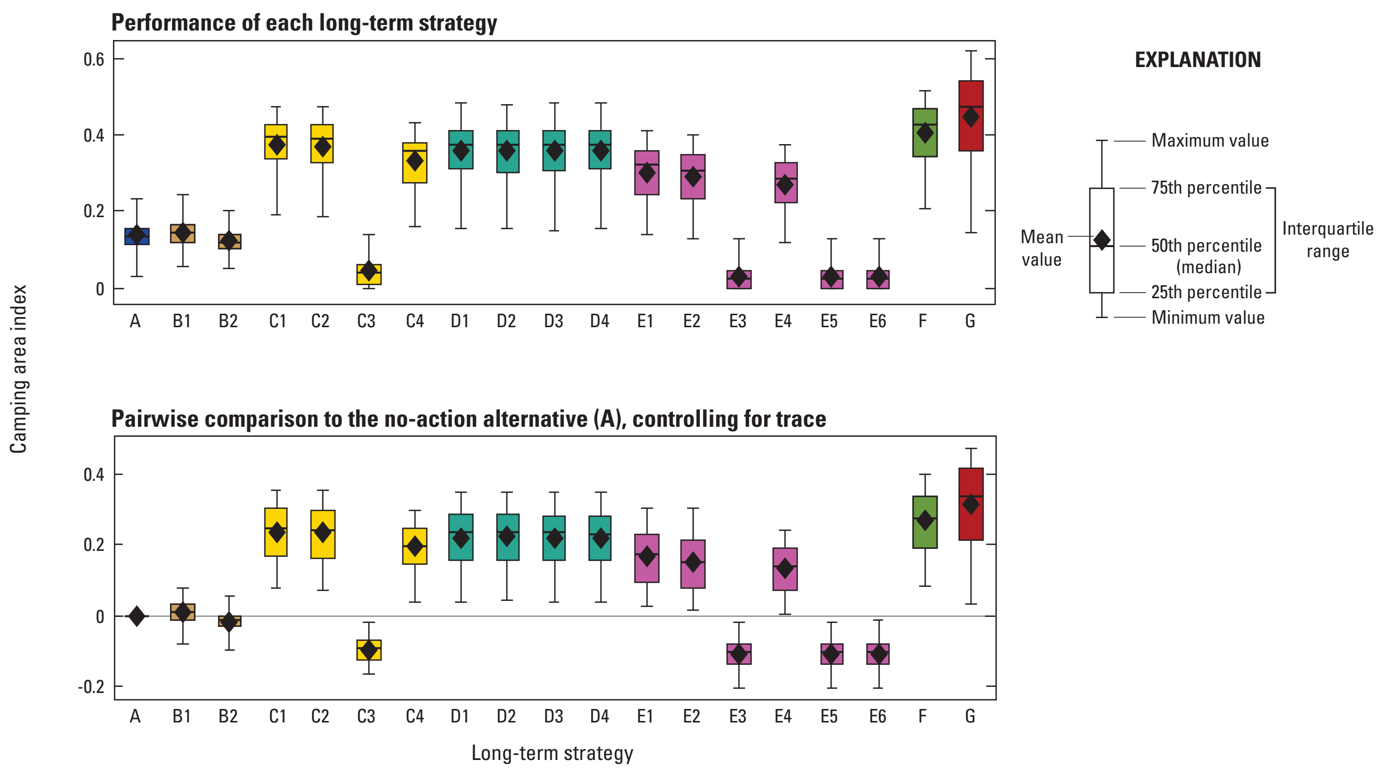

Figure 14. Camping area index (performance metric 11) forecast for 19 long-term strategies with equal weighting of traces.

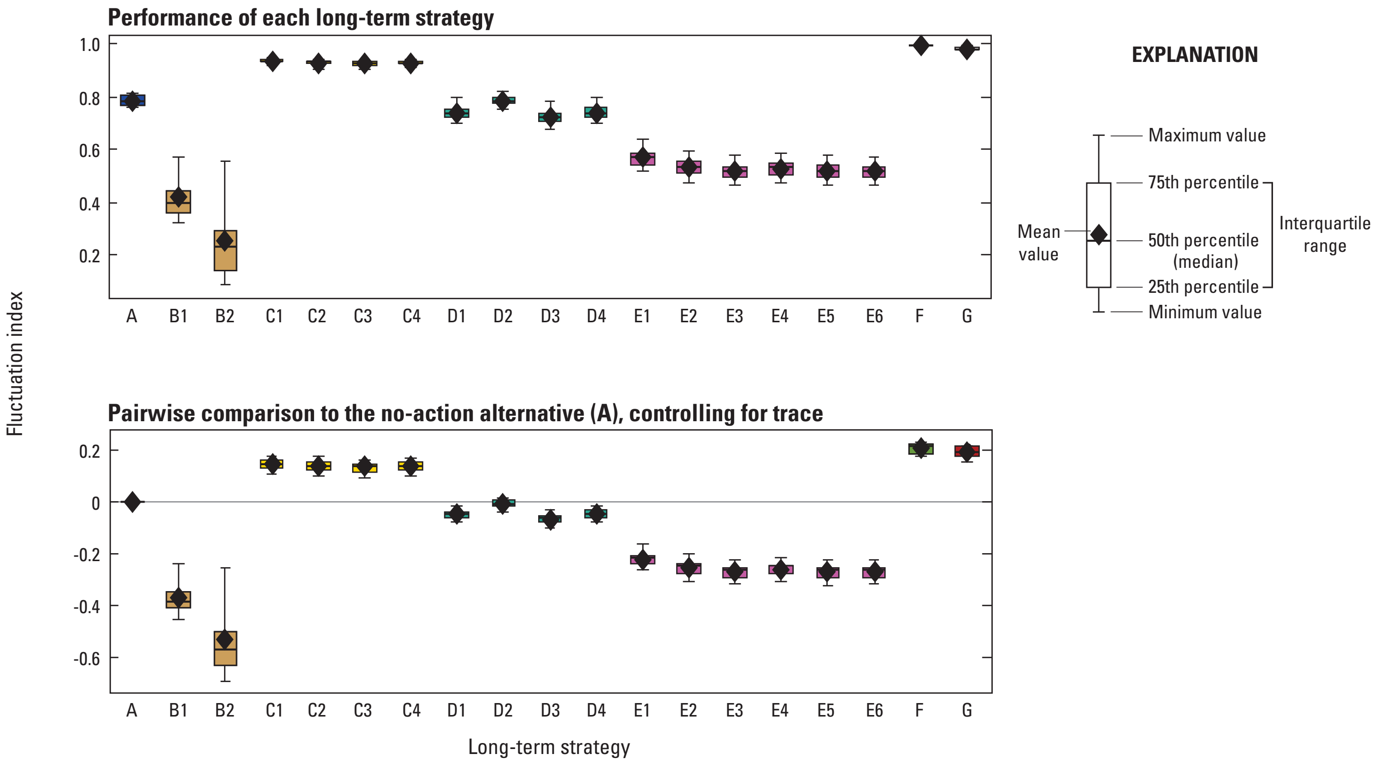

Figure 15. Fluctuation index (performance metric 12) forecast for 19 long-term strategies with equal weighting of traces.

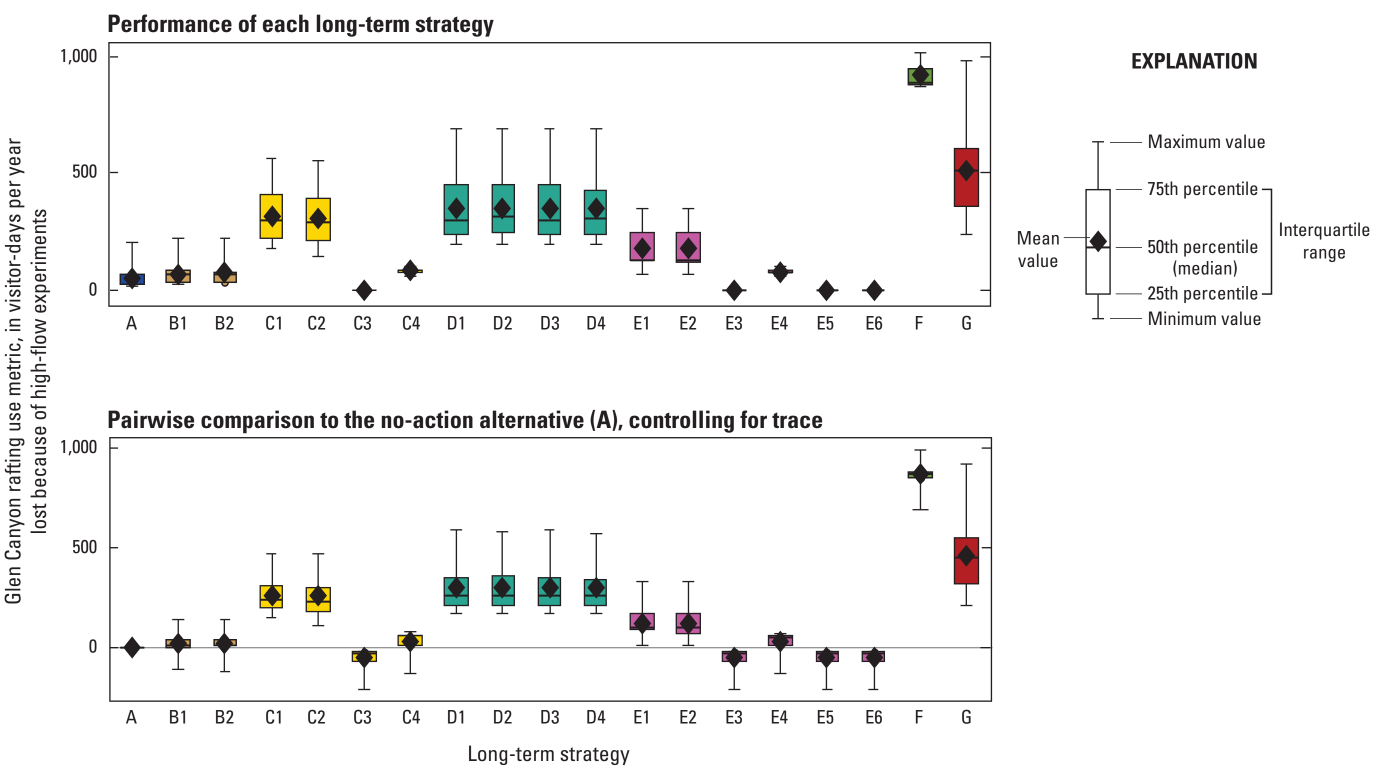

Figure 16. Glen Canyon rafting use metric (performance metric 13) forecast for 19 long-term strategies with equal weighting of traces.

The index ranged between 2 and 6 across alternatives and traces (fig. 17), indicating a 50-percent degradation or a 50-percent improvement in vegetation conditions, respectively. The highest mean vegetation index was associated with long-term strategy D4 (riparian vegetation index, 3.954), but 13 of the 19 long-term strategies were ranked first depending on the hydrological and sediment trace. The value of information for resolving uncertainty about the hydrological and sediment trace before committing to a long-term strategy was 0.224 (an improvement of 5.66 percent; table 6). The choice of the long-term strategy was not affected, however, by any of the critical uncertainties (table 6).

7.7 Sediment Results

The SLI (performance metric 15) measured the potential for sand bar formation by reporting the proportion of sand transported during flows greater than 31,500 ft^3/s. The SLI was most strongly affected by the frequency of HFEs; the long-term strategies with the highest SLI (especially C1, C2, D1, D2, F, and G) allowed frequent HFEs, and the long-term strategies with the lowest SLI (C3, E3, E5, and E6) did not permit HFEs (fig. 18). Uncertainty in the combination of hydrological and sediment trace did affect the ranking of the alternatives (EVXI, 3.57 percent; table 6) with 6 of the 19 long-term strategies favored in at least 1 trace.

7.8 Tribal Resources Results

Several performance metrics were developed to evaluate resources of specific importance from a tribal perspective. The marsh vegetation ratio (performance metric 16) forecast the preservation or expansion of the wetland vegetation communities along the Colorado River (fig. 19). For context, the current extent of marsh vegetation is 4.6 acres. The long-term strategy with the highest mean marsh vegetation ratio was E6 (mean marsh vegetation ratio, 1.101), representing about a 10-percent increase in marsh community area, but long-term strategy E3 was most commonly ranked first among the 63 traces. Alternatives C, F, and G exhibited consistent losses of marsh vegetation compared to Alternative A, whereas Alternatives D and E exhibited modest increases (fig. 19). The variance in the index induced by variation in hydrology was larger than the variance across alternatives (fig. 19). The value of information for resolving hydrological and sediment uncertainty before committing to a long-term strategy was 3.20 percent (table 6).

The frequency of mechanical removal (performance metric 17) was 0 for those long-term strategies that do not permit this management tool (C1, C2, E1, E2, E5, E6, and F) and varied between 0 and 6 years out of 20 for the other long-term strategies (fig. 20). For those long-term strategies that permitted mechanical removal, the frequency was influenced by the emigration rate of RBT from Glen Canyon (performance metric 4), which in turn was influenced by the frequency of HFEs. Because the long-term strategies with the lowest frequency were determined simply by whether mechanical removal was allowed or not, the identification of the top-ranked strategy was not influenced by any of the uncertainties.

The frequency of trout management flows (performance metric 18) was 0 for those long-term strategies that did not allow their use (10 out of the 19 long-term strategies) and varied between 0 and 20 years out of 20 for the remaining strategies (fig. 21). Under Alternative G, TMFs were triggered on average more than one-half of the years, and sometimes in all 20 years, depending on the hydrological trace. For the strategies that allowed TMFs, the frequency of their use was correlated with RBT abundance and, hence, with the RBT catch rate (performance metric 3) and emigration rate (performance metric 4). Again, because the long-term strategies with the lowest frequency of TMFs were determined by the admissible tools in the strategy, the value of information associated with the various uncertainties was 0.

7.9 Full Consequence Table

A summary of the performance of the 19 long-term strategies against the 18 performance metrics is represented in a consequence table (table 7). There is neither a single long-term strategy that performs best for all performance metrics (such a strategy would be shaded in yellow across the corresponding row), nor a single long-term strategy that performs worst for all performance metrics (such a strategy would be shaded dark blue across the row); furthermore, no long-term strategy is either consistently better or consistently worse than Alternative A across all performance metrics. Interestingly, the strategies that are worst for a number of performance metrics (for example, B2, C3, E5, F, and G) are also best for other performance metrics. Other long-term strategies are neither best nor worst on any performance metrics (for example, B1, C4, D1, D2). This pattern of performance indicates that there are important tradeoffs among the long-term strategies, and the best alternative cannot be identified without considering the relative value of the resource goals and performance metrics.

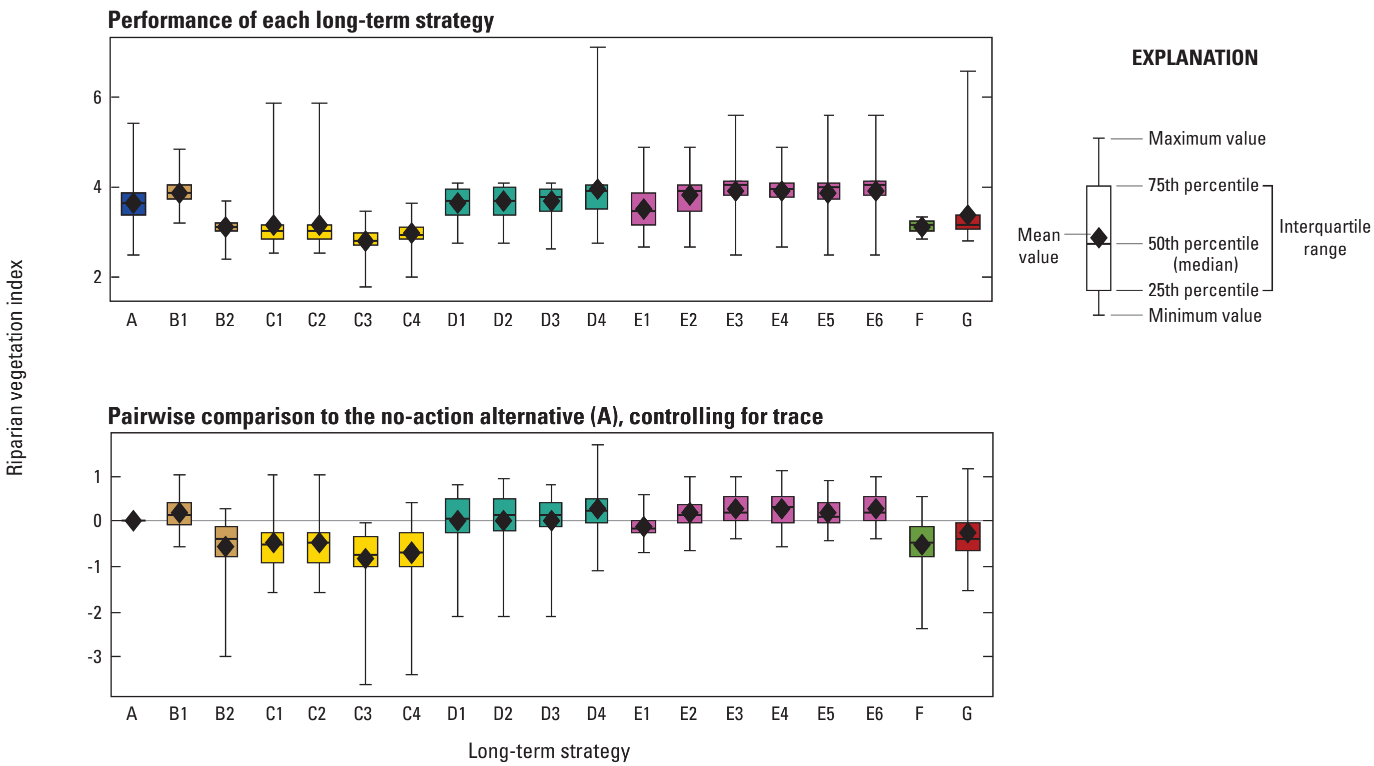

Figure 17. Riparian vegetation index (performance metric 14) forecast for 19 long-term strategies with equal weighting of traces.

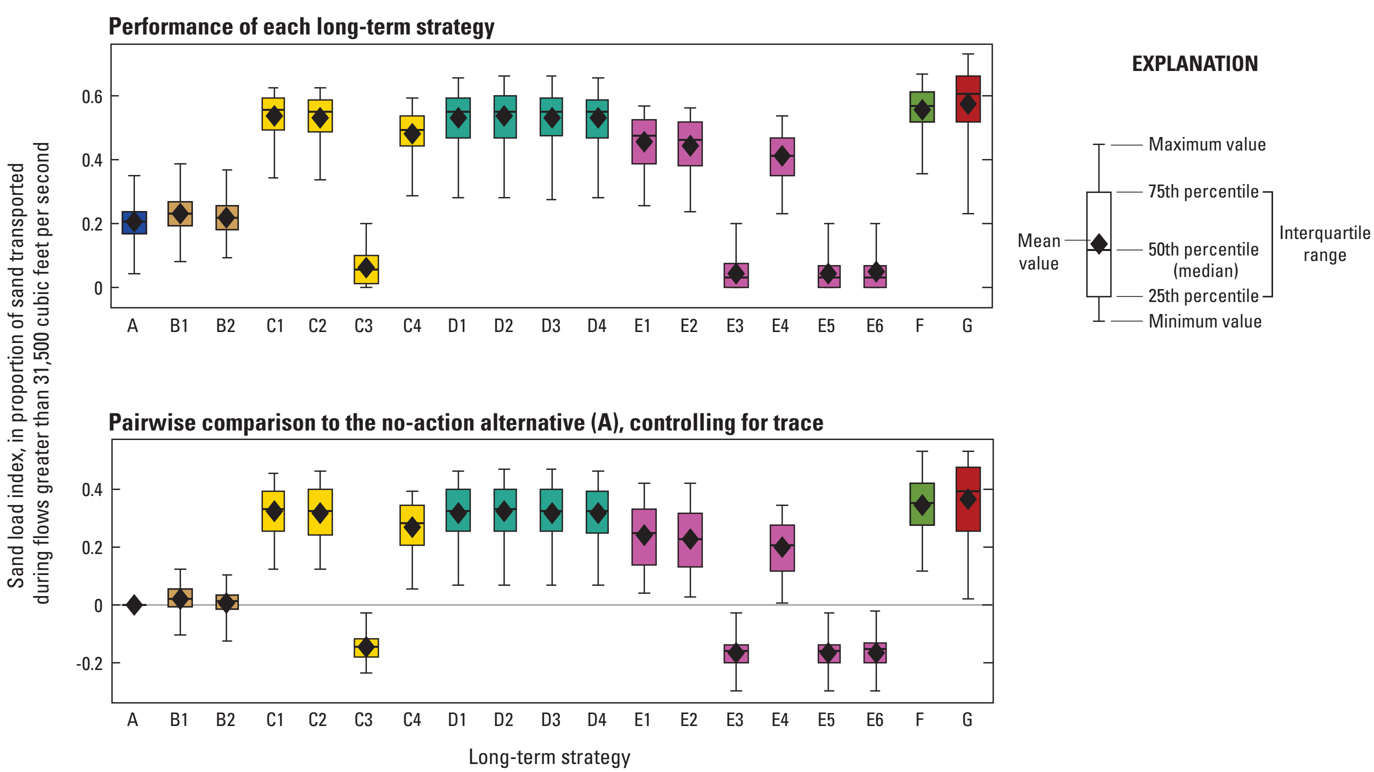

Figure 18. Sand load index (performance metric 15) forecast for 19 long-term strategies with equal weighting of traces.

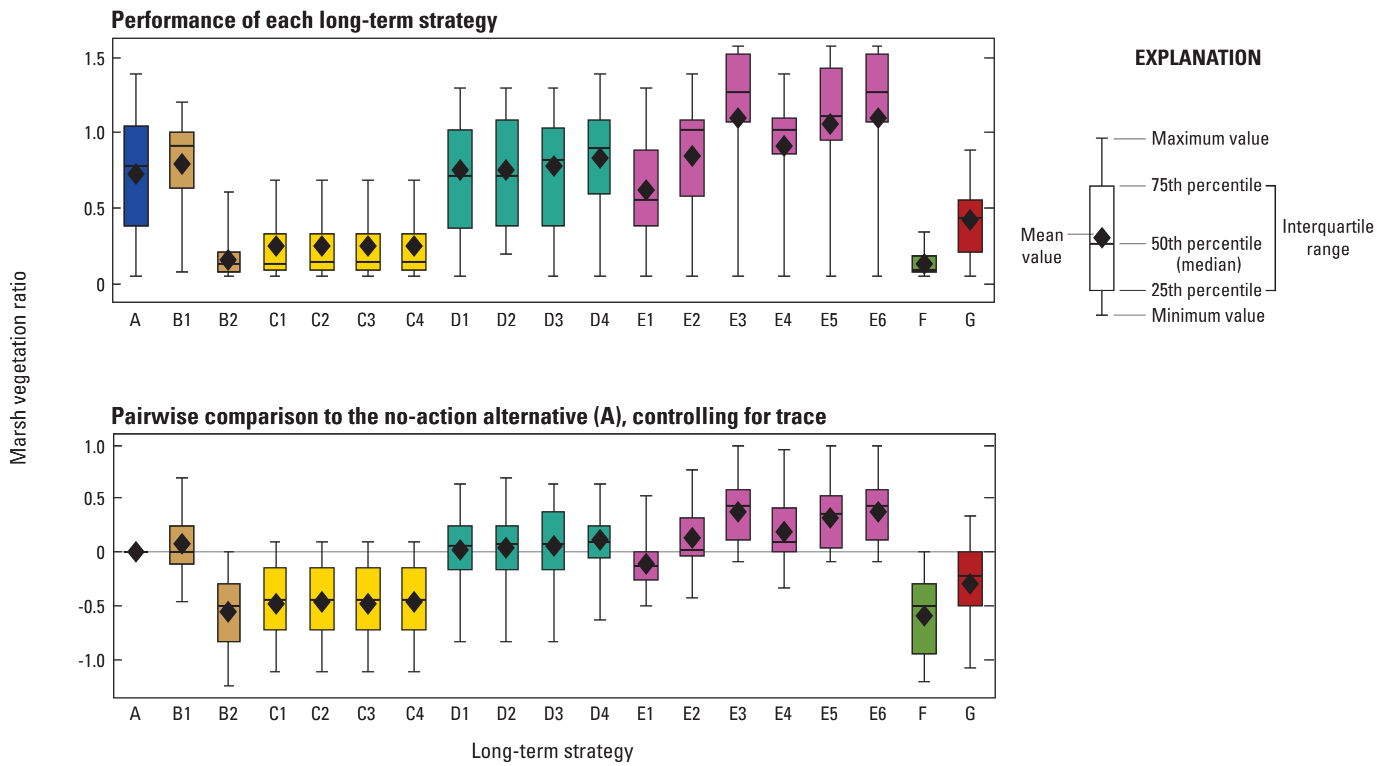

Figure 19. Marsh vegetation ratio (ratio of average marsh cover over 20-year period to current marsh cover, performance metric 16) forecast for 19 long-term strategies with equal weighting of traces.

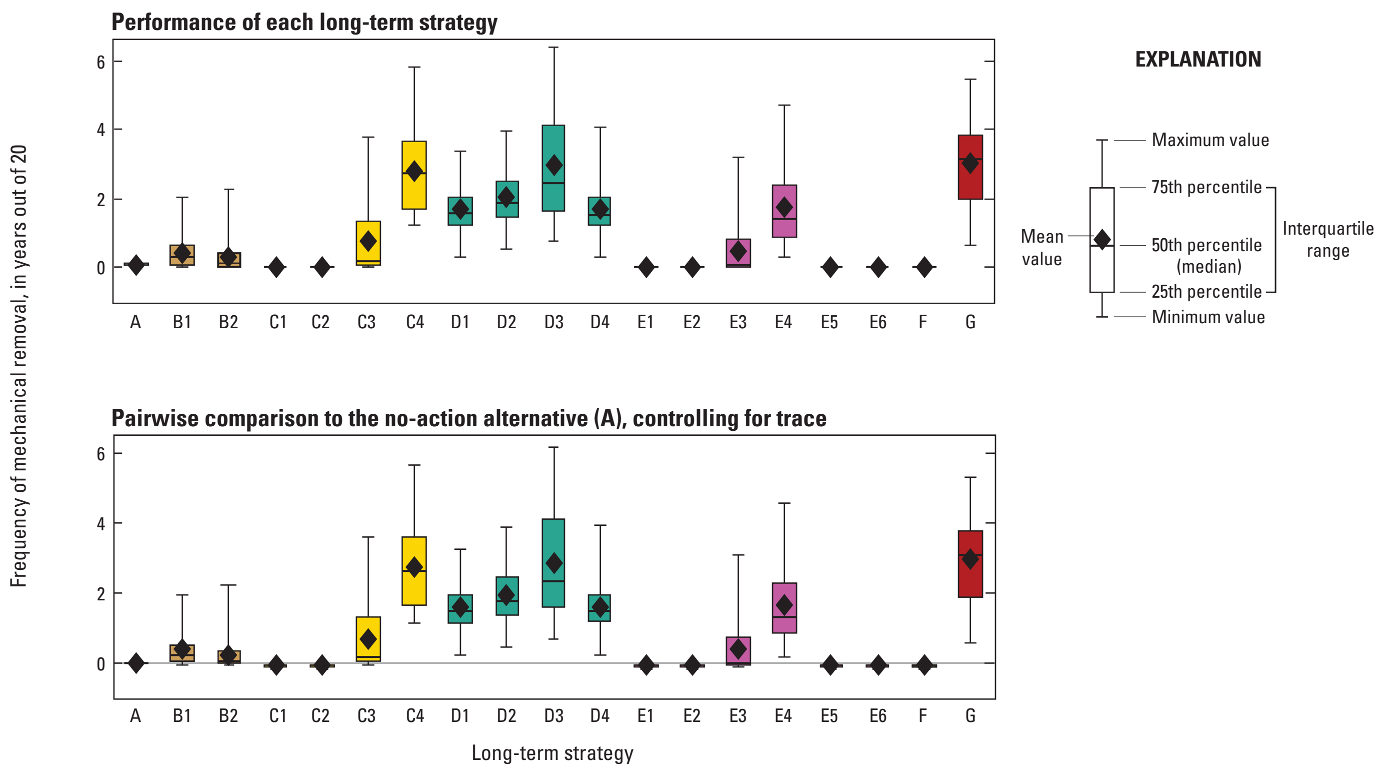

Figure 20. Frequency of mechanical removal (performance metric 17) forecast for 19 long-term strategies with equal weighting of traces.

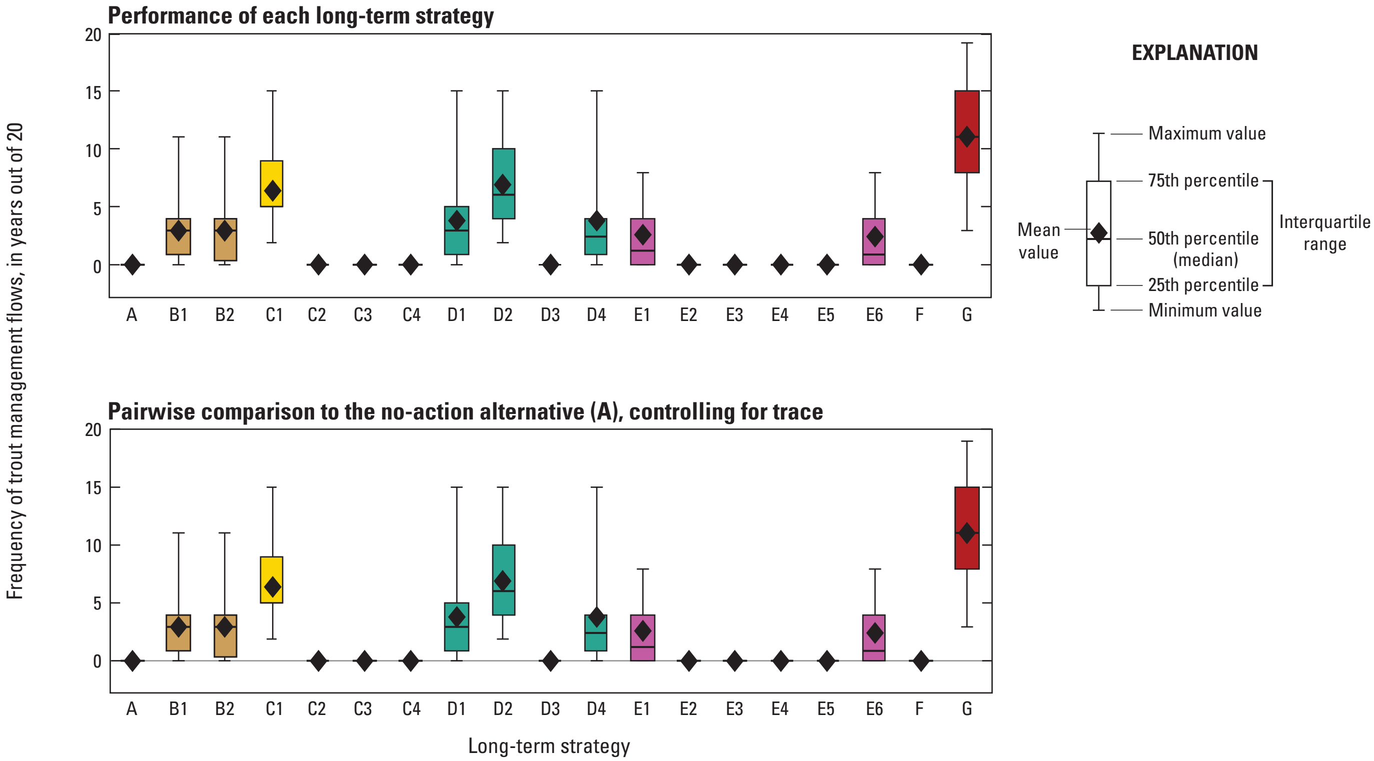

Figure 21. Frequency of trout management flows (performance metric 18) forecast for 19 long-term strategies with equal weighting of traces.

Table 7. Full consequence table showing the mean value of each performance metric for each long-term strategy.

[The columns are the performance metrics, numbered as in table 1. For most performance metrics, higher values are desired (yellow), but for five metrics, lower values are desired (pink). The rows are the long-term strategies. The values in each column are color-coded, with the best-performing long-term strategy shaded in yellow, the worst-performing long-term strategy shaded in dark blue, strategies that perform better than status quo (Alternative A) shaded in orange, and strategies that perform worse than status quo shaded in turquoise. HBC, humpback chub; TempSuit, temperature suitability index; RBT, rainbow trout; WTSI, wind transport of sediment index; GC flow, Glen Canyon flow index; TOR, time-off-river index; CAI, camping area index; FI, fluctuation index; GC raft, Glen Canyon rafting use metric; Veg, riparian vegetation index; SLI, sand load index; MR, mechanical removal; TMF, trout management flow]

Long-term strategy	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	HBC	Temp Suit	RBT Catch	RBT Emigrate	Quality RBT	WTSI	GC flow	TOR	Power	Cap.	CAI	FI	GC raft	Veg	SLI	Marsh	MR	TMF
	High	High	High	Low	High	High	Low	High	High	High	High	High	Low	High	High	High	Low	Low
A	4,991	0.097	2.11	36,699	769	0.159	22.7	0.823	148.5	28.5	0.139	0.786	49	3.66	0.211	0.72	0.07	0.0
B1	5,392	0.097	1.67	29,586	867	0.171	23.1	0.823	149.4	30.4	0.146	0.420	71	3.87	0.234	0.80	0.44	3.0
B2	5,541	0.097	1.46	24,172	920	0.144	23.1	0.823	150.4	32.4	0.122	0.256	72	3.12	0.222	0.17	0.30	3.1
C1	5,016	0.082	2.23	43,683	748	0.377	21.8	0.824	147.3	20.8	0.376	0.935	315	3.18	0.536	0.25	0.00	6.5
C2	4,527	0.079	3.18	66,890	640	0.365	21.8	0.823	147.2	19.5	0.371	0.929	307	3.18	0.534	0.25	0.00	0.0
C3	5,335	0.079	1.90	33,559	830	0.043	18.5	0.821	148.9	20.8	0.043	0.924	0	2.83	0.065	0.25	0.74	0.0
C4	4,874	0.079	2.72	55,076	707	0.334	21.0	0.823	147.6	20.8	0.335	0.928	83	2.98	0.483	0.25	2.80	0.0
D1	5,247	0.094	2.02	40,784	811	0.379	23.5	0.835	146.6	23.8	0.359	0.741	348	3.67	0.531	0.75	1.67	3.9
D2	5,181	0.095	2.15	43,981	796	0.378	23.6	0.835	146.1	19.6	0.360	0.784	351	3.69	0.535	0.76	2.02	6.9
D3	4,876	0.095	2.63	55,811	711	0.378	23.5	0.836	146.8	23.8	0.359	0.724	348	3.70	0.533	0.78	2.95	0.0
D4	5,241	0.097	2.03	40,936	810	0.380	23.5	0.836	146.7	25.1	0.358	0.741	348	3.95	0.529	0.84	1.69	3.8
E1	5,269	0.090	1.93	37,614	826	0.311	21.3	0.839	148.0	22.8	0.303	0.568	177	3.54	0.456	0.62	0.00	2.6
E2	5,015	0.086	2.33	47,450	761	0.297	21.3	0.837	147.9	21.8	0.292	0.534	174	3.84	0.443	0.85	0.00	0.0
E3	5,477	0.087	1.68	28,499	891	0.030	18.4	0.836	149.3	22.8	0.028	0.517	0	3.93	0.046	1.10	0.47	0.0
E4	5,103	0.087	2.19	42,806	781	0.281	20.9	0.838	148.1	22.8	0.272	0.529	79	3.93	0.415	0.91	1.73	0.0
E5	5,470	0.083	1.68	28,561	890	0.029	18.5	0.835	149.1	21.8	0.028	0.517	0	3.87	0.046	1.05	0.00	0.0
E6	5,708	0.087	1.42	22,415	956	0.032	18.8	0.837	149.3	22.8	0.030	0.518	0	3.93	0.049	1.10	0.00	2.4
F	4,450	0.030	3.37	71,869	592	0.299	36.8	0.749	141.0	11.2	0.406	0.997	919	3.14	0.558	0.14	0.00	0.0
G	4,741	0.102	2.81	58,533	702	0.465	24.7	0.840	142.9	18.0	0.451	0.981	512	3.40	0.576	0.42	3.05	11.0

8 Decision Analysis Results

The purposes of completing a formal decision analysis as a component of the evaluation in the LTEMP EIS was to explicitly examine the influence of the relative importance assigned to the resource goals on the ranking of the alternatives and long-term strategies, and to understand the effect of uncertainty on this same ranking. As described in section 3, "Decision Analysis," the two primary tools used to support this investigation were MCDA and the expected value of information.

8.1 Swing-Weighting Method and Results

The swing-weighting method (Winterfeldt and Edwards, 1986) was used to develop weights for the performance metrics, reflecting individual stakeholder expressions of the relative importance of those metrics. In April 2014, a 2-day workshop was held to present a preliminary analysis of the long-term strategies against the performance metrics to interested stakeholders. After discussion of the meaning and interpretation of each of the performance metrics, the stakeholders were given a swing-weighting response form with instructions (table 8) to complete within several weeks. The swing-weighting method asks a decision maker or stakeholder to consider each resource goal, the performance metric that reflects it, and the range over which the performance metric varies; and to compare the relative importance of the performance metrics by evaluating how valuable it would be to change the performance of an alternative from the worst score for a performance metric to the best score. The stakeholders were first asked to rank the performance metrics in this manner and then to assign a score between 0 and 100 to each metric to reflect a more nuanced interpretation of the ranking. Because it is difficult to evaluate 18 performance metrics simultaneously, and because there were natural groupings of the metrics, the swing-weighting exercise used a two-level structure. The 18 performance metrics were assigned to 8 higher-level groups (table 8). The stakeholders first ranked and scored the metrics within each group. Then, to rank and score the higher-level groups, the stakeholders were asked to think about the importance of changing the scores of all the metrics within a group for their worst levels to their best levels at the same time. While completing this exercise, the stakeholders had access to a preliminary consequence table (similar to table 7) and a spreadsheet that automatically calculated the weights on the performance metrics as the swing-weighting sheet was filled in.

A total of 27 Federal, State, tribal, and private agencies and organizations were invited to participate in the decision analysis by expressing their view of the relative importance of the performance metrics using the swing-weighting method (Winterfeldt and Edwards, 1986). The invitations were sent to agencies that were either members of AMWG or Cooperating Agencies for the LTEMP EIS; 14 agencies, including the 2 joint-lead agencies, elected to participate (table 9).

From the responses to the swing-weighting exercise, weights were calculated for the 18 performance metrics separately for each participating stakeholder. To compare these vectors of weights, principal components analysis was used to reduce the dimension of the comparison from 18 to 2. The first two principal components explained 52.6 percent of the variation in weights across stakeholders. The first principal component was positively correlated with the weight on the frequency of mechanical removal, SLI, WTSI, fluctuation index, and riparian vegetation index; and negatively correlated with hydropower generation and capacity (fig. 22*A*). The second principal component was positively correlated with HBC population size, Glen Canyon rafting use, and the camping area index; and negatively correlated with RBT emigration and the Glen Canyon flow index (fig. 22*A*). The differences among the participating stakeholders can then be plotted with these two components (fig. 22*B*). Representatives from the utility industry (CREDA, UAMPS, and SRP) tended to put more weight on the hydropower generation and capacity metrics than other stakeholders. The agencies concerned with management of the RBT fishery (International Federation of Fly Fishers [IFFF] and Arizona Game and Fish Department [AZGFD]) were in the middle of the spectrum on the first component but had strong positive values for the second component, reflecting an emphasis on HBC, high-quality RBT, and RBT catch rate. The FWS, Arizona Department of Water Resources (ADWR) and the Hopi, Hualapai, and Navajo Tribes placed relatively more emphasis on increasing vegetation and minimizing RBT emigration than other stakeholders. The principal components for two of the nongovernment organizations (Grand Canyon River Guides [GCRG] and National Parks Conservation Association [NPCA]) placed an emphasis on camping area index, SLI, and WTSI. Note that the joint-lead agencies (Reclamation and NPS) separately completed the swing-weighting exercise, and their separate weights were used as input to the principal components analysis, but they elected to average their weighting vectors for presentation and discussion. The joint-lead principal components fall near the center of the spectrum of stakeholders. Although some of these patterns compare well with the expressed views of the stakeholder agencies, others are harder to explain; it is important to note that the higher-order principal components still contained explanatory power, so not all the differences among agencies can be summarized with the first two components.

8.2 Multicriteria Decision Analysis

The weights on the performance metrics, unique to each agency, tribe, or organization, were combined with the consequence table to generate a weighted performance metric for each long-term strategy, allowing a comparison of the long-term strategies that integrates the differences in response across performance metrics and the relative value

Table 8. Swing-weighting response form.

[Stakeholder agencies were invited to share their perspectives on the relative importance of the resource goals and performance metrics using this swing-weighting exercise. The results were compiled to generate agency-specific weights on the performance metrics; GLCA, Glen Canyon National Recreation Area; GRCA, Grand Canyon National Park; min, minimum; M, million; B, billion; >, greater than; yr, year; hr, hour; #, number; TMF, trout management flow]

Agency:

Participants:

Goal	Performance metrics	Units	Desired direction	Worst case	Best case	Higher level Rank	Higher level Score	Sublevel Rank	Sublevel Score
Humpback chub									
	Number of adult humpback chub (20-yr min)	# of adults	High	3,000	8,500				
	Temperature suitability index (river mile 157 and 213)	index (0–1)	High	0	0.20				
Rainbow trout fishery									
	Angler catch rate index	fish/angler-hr	High	1.0	5.0				
	Lees Ferry trout emigration estimate	trout/yr	Low	125,000	15,000				
	Number of trout > 16 inches total length	# fish	High	400	1,200				
Archaeological and cultural resources									
	Wind transport of sediment index (WTSI)	index (0–1)	High	0	0.50				
	GLCA flow effects of historic properties	days flow > 23.2k	Low	75	0				
	Time-off-river index (TOR)	index (0–1)	High	0.60	0.95				
Hydropower									
	Value of energy generation (mean annual)	Million $/yr Billion $/20-yr	High	120M/ 2.4B	200M/ 4B				
	Value of capacity (mean annual)	Million $/yr Billion $/20-yr	High	10M/ 0.2B	50M/ 1B				
Recreation									
	GRCA camping area index (average of 3)	index (0–1)	High	0	0.50				
	Fluctuation index	index (0–1)	High	0	1.0				
	GLCA rafting use index	boat seats lost/yr	Low	1,300	0				
Riparian vegetation									
	Vegetation index (sum of four ratios)	sum of ratios	High	2.0	6.0			1	100
Sediment									
	GRCA sand load index (sand transported > 31,500)	proportion	High	0	0.6			1	100
Tribal									
	Change in marsh vegetation	ratio	High	0	1.5				
	Mechanical removal (years out of 20)	yrs	Low	5	0				
	Frequency of TMF (years out of 20)	yrs	Low	20	0				

Table 9. Agencies participating in the swing-weighting exercise.

[Representatives from 27 Federal, State, tribal, and private agencies were invited to participate in the swing-weighting exercise. The set of invited agencies included the Adaptive Management Working Group and cooperating agencies for the Long-term Experimental and Management Plan Environmental Impact Statement. Of the 27 agencies invited, 14 participated. AMWG, Adaptive Management Working Group; CA, cooperating agency; NGO, non-governmental organization]

Agency	Affiliation	AMWG	CA	Participant
Bureau of Indian Affairs	Federal	Yes	Yes	No
National Park Service	Federal	Yes	Yes	Yes
Bureau of Reclamation	Federal	Yes	Yes	Yes
U.S. Fish and Wildlife Service	Federal	Yes	Yes	Yes
Western Area Power Administration	Federal	Yes	Yes	No
Havasupai Tribe	Tribe	No	Yes	No
Hopi Tribe	Tribe	Yes	Yes	Yes
Hualapai Tribe	Tribe	Yes	Yes	Yes
Navajo Nation	Tribe	Yes	Yes	Yes
Pueblo of Zuni	Tribe	Yes	Yes	No
Southern Paiute Consortium	Tribe	Yes	No	No
Fort Mojave Indian Tribe	Tribe	No	Yes	No
National Parks Conservation Association	NGO	Yes	No	Yes
International Federation of Fly Fishers	NGO	Yes	No	Yes
Grand Canyon River Guides	NGO	Yes	No	Yes
Arizona Department of Water Resources	State	Yes	No	Yes
Arizona Game and Fish Department	State	Yes	Yes	Yes
Colorado River Board of California	State	Yes	Yes	No
Colorado Water Conservation Board	State	Yes	No	No
Colorado River Commission of Nevada	State	Yes	Yes	No
New Mexico Interstate Stream Commission	State	Yes	No	No
Wyoming State Engineer’s Office	State	Yes	No	No
Utah Division of Water Resources	State	Yes	No	No
Salt River Project	Public power utility	No	Yes	Yes
Upper Colorado River Commission	State and Federal	No	Yes	No
Colorado River Energy Distributors Association	Power purchase contractor	Yes	No	Yes
Utah Associated Municipal Power Systems	Power purchase contractor	Yes	Yes	Yes

the particular agency places on those performance metrics. For the joint-lead agencies, using their average set of weights, Alternative D (and specifically, long-term strategy D4) performed better than the other alternatives (fig. 23). Alternatives C, D, E, F, and G all substantially outperformed Alternative A (status quo), provided HFEs were implemented. The long-term strategies that did not implement HFEs (C3, E3, E5, and E6) were all demonstrably poorer than Alternative A, as measured by the weighted performance. The weighted performance of Alternative B was similar to that of Alternative A, with long-term strategy B1 slightly better than long-term strategy B2.

Alternative D was created after a preliminary analysis of the other alternatives. In the April 2014 preliminary analysis, the results of which were discussed by the joint-lead agencies and the Cooperating Agencies, Alternative C and E exhibited roughly equivalent performance with some differences in ranking across stakeholders. Alternative D was created as a hybrid between Alternative C and E, taking features of each that had contributed to positive performance in the preliminary analysis. One of the advantages of separating objective weighting from alternative evaluation in MCDA is that the weights only depend on the ranges of the performance metrics, not on the alternatives under consideration, so new alternatives can be evaluated without having to re-elicit the swing weights. Because Alternative D was created from the insights gained in the preliminary analysis of alternatives, it stands to reason that Alternative D outperformed Alternatives C and E. It is interesting, however, that the gain in performance is fairly small, suggesting that only marginal gains in performance remain with the management tools available, against the backdrop

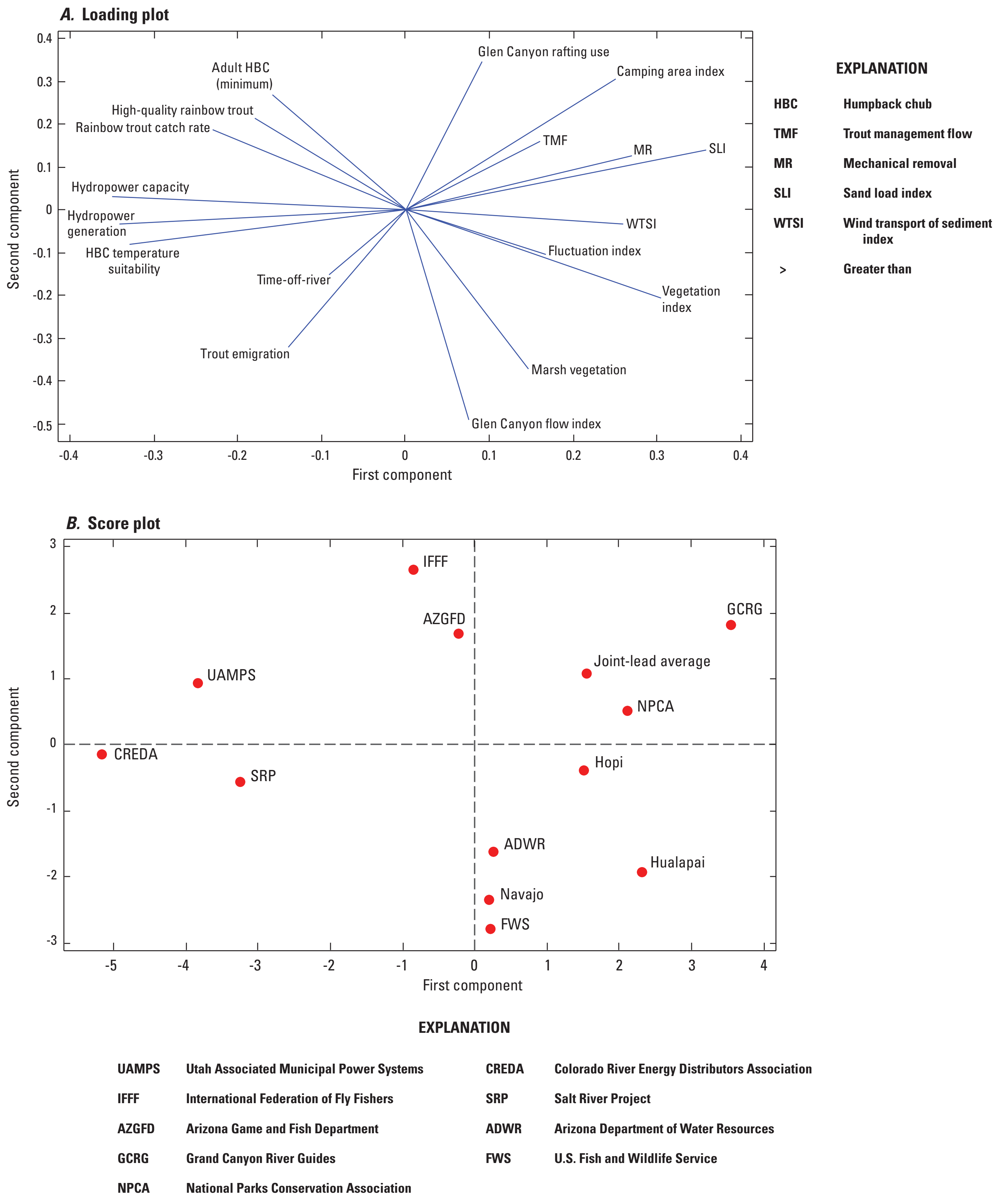

Figure 22. Principal components analysis of the weights on the performance metrics across stakeholder agencies. *A*, loading plot; and, *B*, score plot.

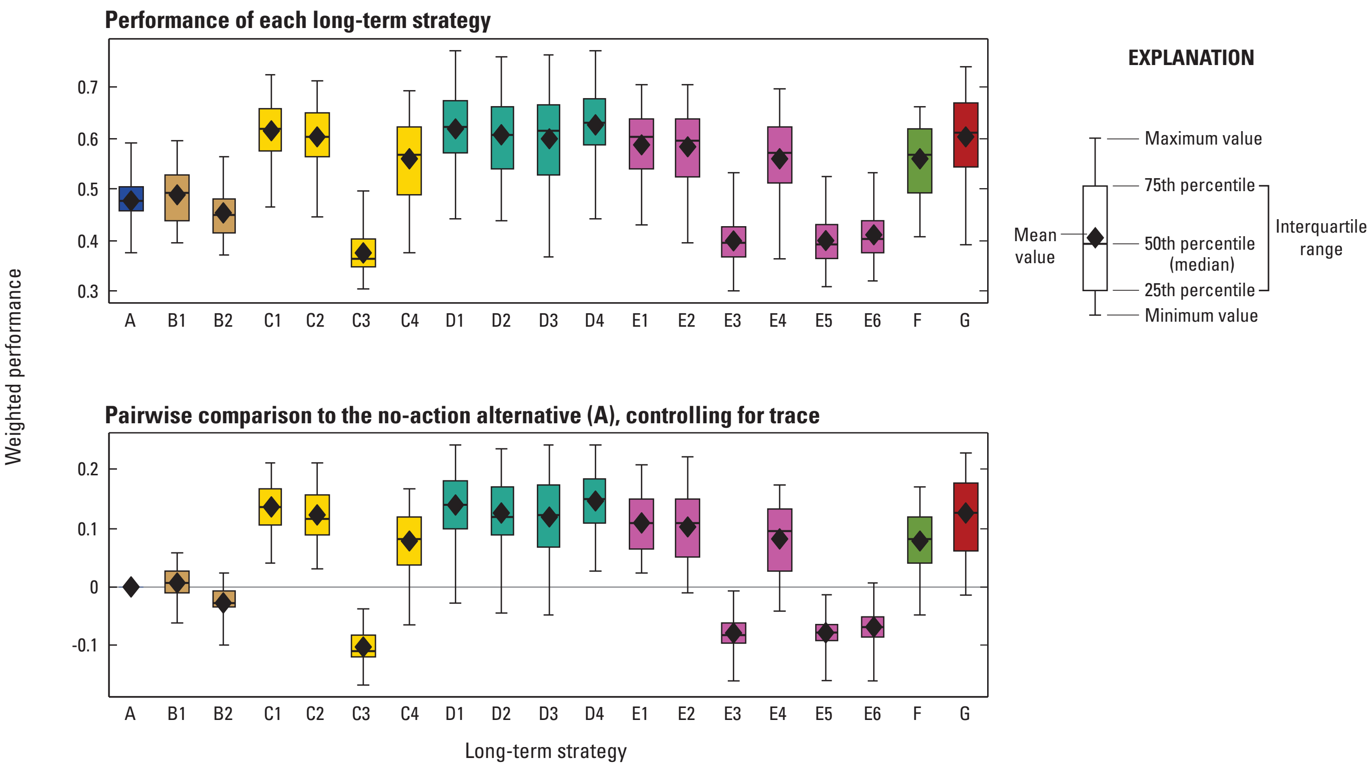

Figure 23. Joint-lead agency weighted performance across 18 metrics forecast for 19 long-term strategies using equal weighting of hydrological traces.

of uncertainty in hydrology and the complex set of tradeoffs among the resource goals.

One of the important motivations for MCDA was the opportunity to include and analyze differing viewpoints from stakeholder agencies regarding the importance of the various resource goals and their performance metrics. The agency-specific weightings did affect the ranking of alternatives (table 10). For most of the participating agencies, long-term strategy D4 had the highest mean-weighted performance (with the mean taken over hydrology and sediment traces and critical uncertainties). For two of the agencies (UAMPS, CREDA), long-term strategy B2 had the highest weighted score, and for one organization (GCRG), Alternative G had the highest weighted score. For all participating agencies except CREDA, long-term strategy D4 outperformed Alternative A. For all agencies, long-term strategy C3 performed worse than Alternative A, and for most of those agencies, it was the worst-performing long-term strategy. Alternative F was a polarizing strategy: for three agencies it was the worst-performing strategy, whereas for four others, it performed better than the status quo. Most of the differences across stakeholders in the MCDA ranking of the long-term strategies can be explained by the first principal component in the weighting (fig. 22). For those agencies that placed more weight on the performance metrics on the left side of the diagram (fig. 22*A*), Alternative B performed very well because it performs best for power generation and capacity; for those agencies that placed more weight on the performance metrics on the right side of the diagram (fig. 22*A*), Alternative B was outperformed by Alternative D. Across all participating stakeholders, the mean values for the long-term strategies in Alternative D were greater than those for Alternatives C and E, suggesting that the improvements made in crafting Alternative D are robust to the weights on the performance metrics.

Across stakeholders, the top-ranked long-term strategy was effectively tied with a number of other long-term strategies, against the backdrop of uncertainty induced by the hydrology and sediment traces; for example, using the joint-lead agency weights on the objectives, Alternative D4 had the highest mean performance, but the differences between D4 and next nine long-term strategies (D1, C1, D2, G, C2, D3, E1, E2, and E4) had ranges that included zero (fig. 24, bottom panel); that is, based on the results of the MCDA, alternatives C, D, E, and G were nearly indistinguishable using the joint-lead agency weights. This pattern held for the weights from most stakeholders as well (fig. 25), with between 2 and 11 long-term strategies effectively tied. For all stakeholders except CREDA, long-term strategies D4 and D1 were either the best-performing or effectively tied with the best-performing long-term strategy.

The differences among the long-term strategies within Alternative D are difficult to discern (fig. 23). The tradeoffs associated with using TMFs are marginal (compare D1 to D3). Similarly, the tradeoffs associated with “bug flows” do not

Table 10. Weighted performance for 19 long-term strategies using the weights on the performance metrics expressed by 14 participating agencies.

[The aggregate scores across performance metrics, weighted using the agency-specific swing-weighting results, are shown for each long-term strategy. For each participating agency, the best-performing long-term strategy is shaded in yellow, the worst-performing strategy is shaded in dark blue, strategies that perform better than Alternative A are shaded in orange, and strategies that perform worse than Alternative A are shaded in turquoise. The 21 hydrological traces were weighted equally. Thirteen additional stakeholder agencies were invited but declined to participate. JL, joint-lead agency average; FWS, U.S. Fish and Wildlife Service; ADWR, Arizona Department of Water Resources; AZGFD, Arizona Game and Fish Department; SRP, Salt River Project; UAMPS, Utah Associated Municipal Power Systems; CREDA, Colorado River Energy Distributors Association; IFFF, International Federation of Fly Fishers; NPCA, National Parks Conservation Association; GCRG, Grand Canyon River Guides]

	JL	FWS	ADWR	AZGFD	SRP	UAMPS	CREDA	Hopi	Hualapai	Navajo	IFFF	NPCA	GCRG
A	0.479	0.508	0.483	0.448	0.472	0.448	0.459	0.515	0.530	0.477	0.508	0.450	0.429
B1	0.488	0.504	0.511	0.450	0.493	0.485	0.474	0.512	0.538	0.495	0.511	0.474	0.443
B2	0.454	0.434	0.447	0.402	0.491	0.495	0.484	0.457	0.477	0.446	0.504	0.416	0.384
C1	0.615	0.539	0.484	0.508	0.458	0.410	0.410	0.574	0.599	0.521	0.544	0.604	0.637
C2	0.602	0.515	0.465	0.518	0.426	0.376	0.391	0.570	0.591	0.511	0.549	0.589	0.631
C3	0.376	0.433	0.378	0.369	0.418	0.400	0.412	0.411	0.410	0.374	0.445	0.315	0.280
C4	0.559	0.507	0.452	0.497	0.441	0.392	0.405	0.532	0.544	0.488	0.529	0.555	0.573
D1	0.619	0.573	0.542	0.540	0.489	0.450	0.436	0.596	0.630	0.559	0.553	0.634	0.648
D2	0.607	0.574	0.526	0.535	0.470	0.424	0.414	0.581	0.615	0.547	0.534	0.630	0.642
D3	0.599	0.557	0.526	0.540	0.472	0.425	0.428	0.584	0.614	0.550	0.544	0.621	0.637
D4	0.628	0.590	0.560	0.553	0.500	0.460	0.445	0.610	0.646	0.574	0.559	0.647	0.662
E1	0.589	0.535	0.522	0.506	0.475	0.447	0.430	0.572	0.607	0.535	0.550	0.587	0.592
E2	0.583	0.539	0.533	0.515	0.459	0.428	0.418	0.579	0.616	0.542	0.547	0.588	0.594
E3	0.400	0.488	0.482	0.411	0.450	0.445	0.434	0.463	0.483	0.445	0.461	0.373	0.319
E4	0.560	0.543	0.532	0.509	0.468	0.436	0.427	0.563	0.597	0.536	0.534	0.575	0.569
E5	0.401	0.482	0.476	0.407	0.442	0.438	0.426	0.461	0.482	0.440	0.461	0.370	0.318
E6	0.412	0.498	0.492	0.415	0.460	0.462	0.440	0.469	0.491	0.451	0.467	0.382	0.326
F	0.559	0.465	0.396	0.484	0.311	0.269	0.293	0.509	0.536	0.431	0.475	0.535	0.622
G	0.605	0.559	0.478	0.532	0.456	0.385	0.397	0.563	0.588	0.524	0.514	0.634	0.669

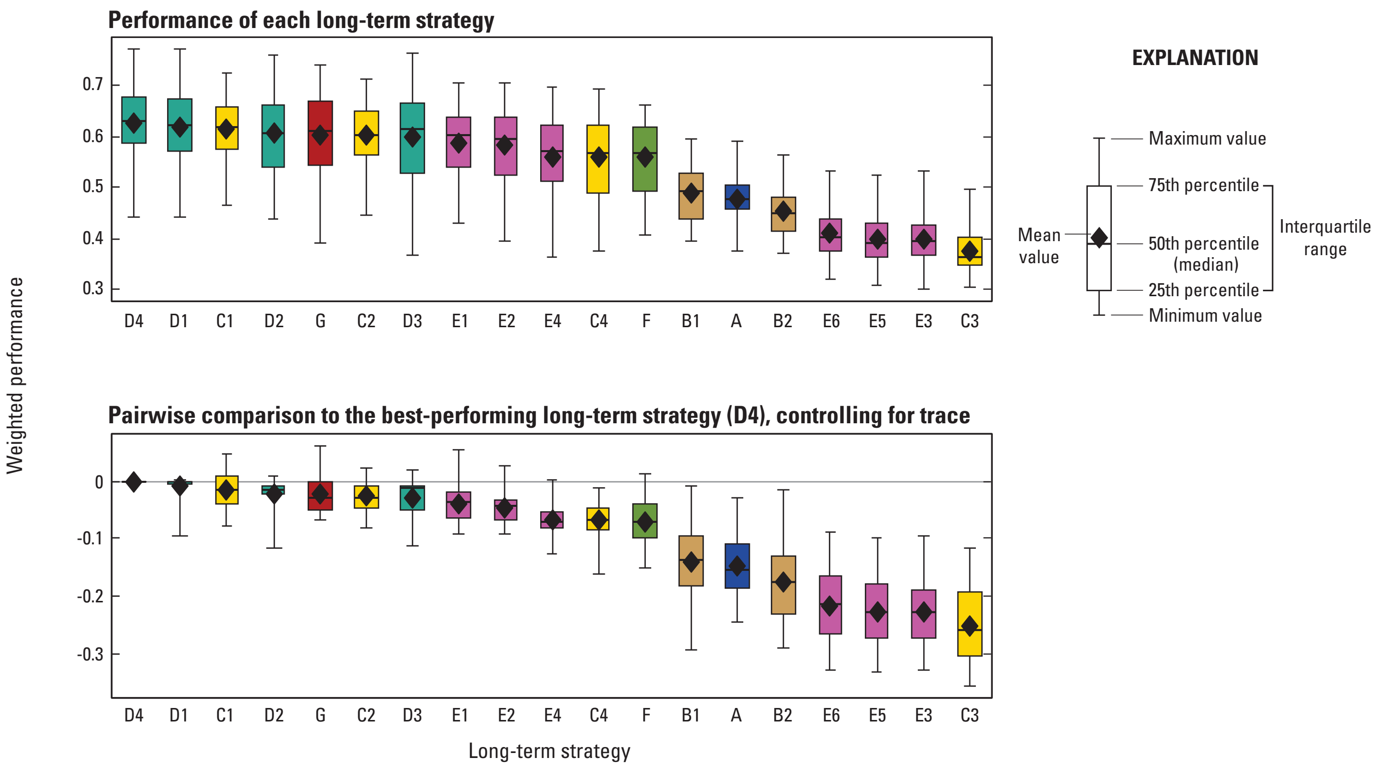

Figure 24. Joint-lead agency weighted performance across 18 metrics, sorted by mean performance, forecast for 19 long-term strategies using equal weighting of hydrological traces.

produce a clear favorite (compare D1 to D2). Finally, although there is the suggestion that the costs of low summer flows outweigh the benefits (compare D1 to D4), the difference is small against the backdrop of the variation driven by hydrology. The patterns within Alternative D are shown for the joint-lead agency weighting (figs. 23–24) but hold for the other stakeholder weightings as well (fig. 25).

8.3 Expected Value of Information

A second important purpose for the use of formal decision analysis tools was to examine the effect of uncertainty on the ranking of the alternatives. Although the effect of uncertainty on the ranking of alternatives based on single performance metrics was generally small (table 6), it is conceivable that the weighted performance could be more sensitive to uncertainty if the effects of the uncertainties affect the subtle balancing of tradeoffs. The analysis of the value of information on the weighted performance, however, revealed that the effect of the uncertainties was nearly 0 (table 11). For the joint-lead agency weighting and all but two of the participating stakeholders, the best-performing long-term strategy was the same across the 16 hypotheses that represented critical uncertainty (table 11); for example, long-term strategy D4 was preferred in the joint-lead agency weighting regardless of whether fall HFEs have an effect on RBT recruitment or not, regardless of whether TMFs are 10 or 50 percent effective in reducing RBT recruitment, and regardless of the relative influence of temperature and RBT on juvenile HBC survival and growth. For two stakeholders, there was a very small effect of the critical uncertainty: for IFFF, C2 was preferred more than D4 in 2 of the 16 hypotheses; and for GCRG, D4 was preferred more than G in 1 of the 16 hypotheses (table 11). Even in these two cases, however, the expected value of information for resolving the uncertainty represented by the 16 hypotheses was less than 0.1 percent.

At first glance, these results may seem puzzling. Many intense discussions within AMWG through the years have focused on concern that uncertainty about the response of the system to management prevents the identification of a best management strategy, and differences concerning recommendations for management have been explained as differences in interpretation of the scientific evidence. The uncertainties examined in this analysis (effect of fall HFEs, effectiveness of TMFs, and relative influence of temperature and RBT on juvenile HBC) have been central to previous discussions. But the results of this analysis do not support the conclusions that resolution of this uncertainty is important in choosing among the long-term strategies examined. There are several explanations for these results. First, there is less uncertainty than informal conversations imply. After several decades of intense study of the resources affected by the operation of Glen Canyon Dam, the AMWG partners have learned a great deal. Uncertainty remains, of course, but it is bounded; for

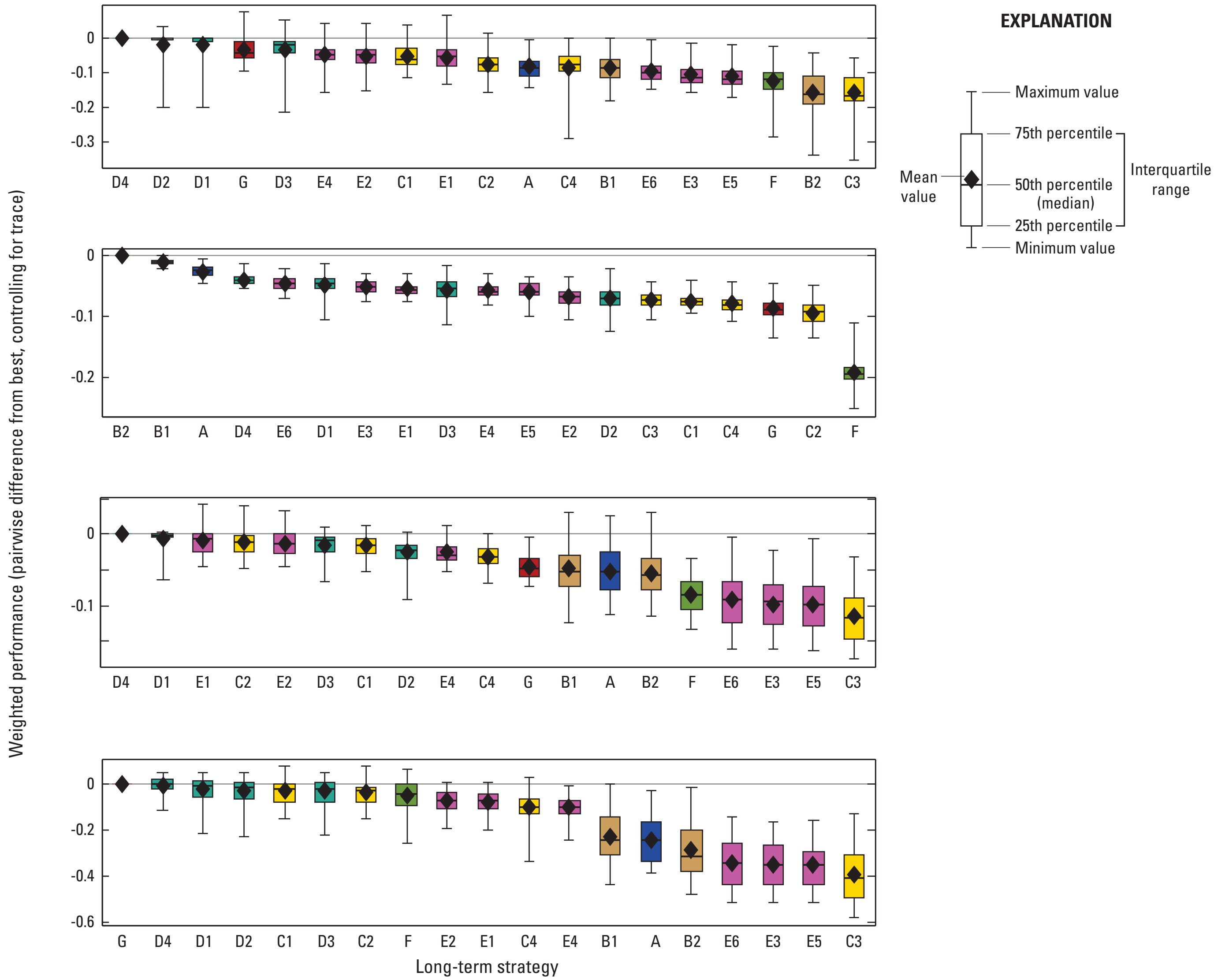

Figure 25. Weighted performance across 18 metrics, for four stakeholder agencies, sorted in descending order of mean performance. The four panels show the results for the stakeholders at the outer boundary of the score plot (fig. 22B; U.S. Fish and Wildlife Service, Colorado River Energy Distributors Association, International Federation of Fly Fishers, and Grand Canyon River Guides).

Table 11. Expected value of perfect information for resolving various uncertainties, as a function of the agency-specific weights.

[For each of the 16 combinations of hypotheses that describe the critical uncertainties, the best-performing long-term strategies are listed, using the agency-specific weights on the performance metrics. The shading of each cell is associated with the alternative from which the best-performing long-term strategy comes. See table 4 for a description of the critical uncertainties. The expected value of information for resolving critical uncertainty is zero for all the stakeholders except IFFF and GCRG. The expected value of partial information for resolving uncertainty about the combination of sediment and hydrology trace, sediment trace alone, and hydrology trace alone is shown. JL, joint-lead agency average; FWS, U.S. Fish and Wildlife Service; ADWR, Arizona Department of Water Resources; AZGFD, Arizona Game and Fish Department; SRP, Salt River Project; UAMPS, Utah Associated Municipal Power Systems; CREDA, Colorado River Energy Distributors Association; IFFF, International Federation of Fly Fishers; NPCA, National Parks Conservation Association; GCRG, Grand Canyon River Guides; HFE, high-flow experiment; TMF, trout management flow; EV, expected value; EVPI, expected value of perfect information; EVXI, expected value of partial information]

Critical uncertainties			Stakeholder												
			Federal		State					Tribe			NGO		
Fall HFE	TMF	Temp trout	JL	FWS	ADWR	AZGFD	SRP	UAMPS	CREDA	Hopi	Hualapai	Navajo	IFFF	NPCA	GCRG
No	High	f1	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	D4	D4	G
No	High	f2	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	D4	D4	G
No	High	g1	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	D4	D4	G
No	High	g2	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	D4	D4	G
No	Low	f1	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	D4	D4	G
No	Low	f2	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	D4	D4	G
No	Low	g1	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	D4	D4	G
No	Low	g2	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	D4	D4	G
Yes	High	f1	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	D4	D4	G
Yes	High	f2	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	D4	D4	G
Yes	High	g1	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	D4	D4	G
Yes	High	g2	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	D4	D4	G
Yes	Low	f1	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	D4	D4	G
Yes	Low	f2	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	C2	D4	G
Yes	Low	g1	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	D4	D4	D4
Yes	Low	g2	D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	C2	D4	G
Average best			D4	D4	D4	D4	D4	B2	B2	D4	D4	D4	D4	D4	G
EV			0.628	0.590	0.560	0.553	0.500	0.495	0.484	0.610	0.646	0.574	0.559	0.647	0.669
EVPI			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0004	0.0000	0.0000
EVPI, in percent			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.01
EVXI (trace), in percent			1.50	1.39	1.54	1.84	0.89	0.10	0.00	1.06	1.32	1.00	1.23	1.87	2.50
EVXI (sediment), in percent			0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.14	0.00
EVXI (hydrology), in percent			1.10	0.93	1.27	1.58	0.75	0.09	0.00	0.87	1.12	0.80	0.91	1.53	1.89

example, the uncertainty in the effect of temperature and RBT on juvenile HBC is large, in the sense that the parameters governing those relations are uncertain by a factor of two (fig. 3*A* and 3*B*); the trout effect on survival could be as small as -0.15 or as large as -0.4. But, the decades of study of the interactions of RBT and HBC have indicated conclusively that there is an effect of RBT on juvenile HBC survival, and there are effects of both RBT and temperature on juvenile HBC growth. Second, the value of information is strongly affected by the set of alternatives considered. It only asks if the uncertainty impedes the choice of a best alternative from among the set evaluated. It does not ask if there could be another alternative, not yet identified, that would be sensitive to the uncertainty. So, for example, it was thought that the value of low summer flows would be sensitive to the effect of temperature on HBC growth; therefore, C2, for example, might be favored compared to C1 if model f1 holds, but C1 might be favored compared to C2 if model f2 holds. This presumes, though, that low summer flows are triggered in enough years and involve flows low enough to lead to substantial changes in the temperature in the Colorado River at the confluence with the Little Colorado River to produce a demonstrable difference between models f1 and f2; this was not the case. But, if there were another alternative that could produce large differences in temperature (for example, a temperature control device on Glen Canyon Dam), these uncertainties may have played a greater role. Third, in a multiple-objective decision, the influence of the weights on the objectives might override the effect of uncertainties; for example, the costs associated with low summer flows (on recreation and hydropower, for example) may override the potential benefits (to HBC) enough that the effect of the uncertainty does not matter.

8.4 Effects of Climate Change

Although the value of information associated with resolving critical uncertainty was small, there was an indication that the uncertainty associated with hydrological input had some influence on the ranking of the long-term strategies (table 11). For the joint-lead agency weighting, foreknowledge of the hydrological and sediment trace could lead to a 1.5 percent improvement in the weighted performance across objectives (table 11). Such knowledge is not possible because it would require accurate prediction of the monthly precipitation in the Colorado Basin over the next 20 years. But in demonstrating that hydrological input might be important in the selection of a long-term strategy, it raises the question about the potential influences of climate change.

The 21 reconstructed historical hydrological traces that were used in the LTEMP analysis represent possible 20-year sequences if the future is like the recent past (1906-2010). The 112 hydrological traces generated as part of the Basin Study (Bureau of Reclamation, 2012) represent the best current understanding of what might happen because of climate change. Mean annual inflow to Lake Powell is quite different under these two sets of traces (fig. 26). The median flow over the climate-change traces is lower than for the historical traces, although it is within the interquartile range of the historical traces. About 30 percent of the potential future distribution of flows, however, is not captured by the distribution of the historical traces. The historical 20-year trace with the lowest mean inflow has an annual flow of about 8.5 million acre-feet; 30 percent of the climate-change traces fall below this point, suggesting that the set of historical traces may not be representative of future conditions.

To examine part of the potential influence of climate change, a reweighting of the historical traces was calculated to better match the mean and variance of Lake Powell inflow seen in the climate-change traces. The climate-change weighing put about 18 percent of the weight on the single hydrology trace with the lowest input to Lake Powell. This reweighting of the hydrological traces was then used in all the MCDA calculations to examine the effect of those weights on the performance of the long-term strategies. For the joint-lead agency weights on the performance metrics, the weights on the hydrological traces had a small effect on the aggregate performance but did not change the rankings of alternatives (fig. 27). A similar pattern was seen for other stakeholder weightings. Although this result suggests the ranking of alternatives is robust to uncertainty about climate change, it is important to

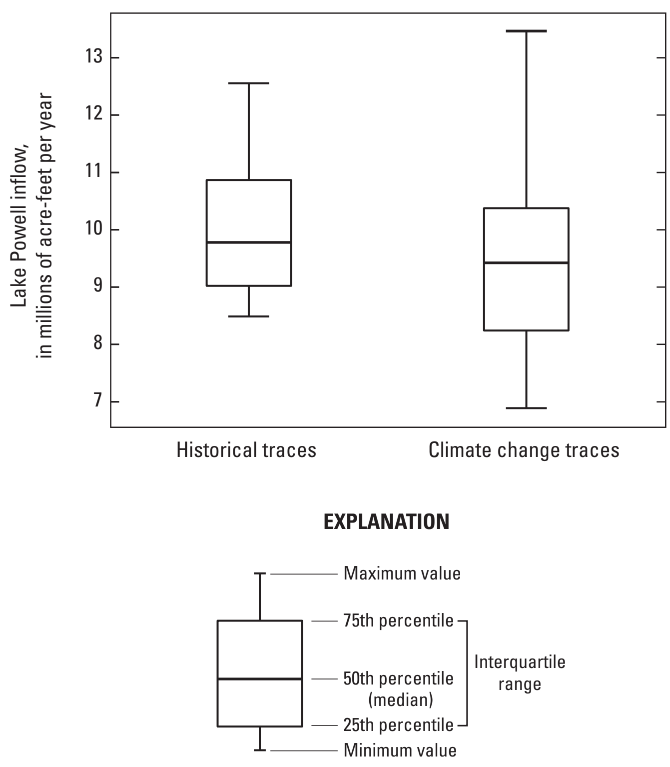

Figure 26. Mean annual inflow to Lake Powell during the 20-year period of the Long-Term Experimental and Management Plan for 21 historical hydrological traces and 112 climate-change-influenced hydrological traces.

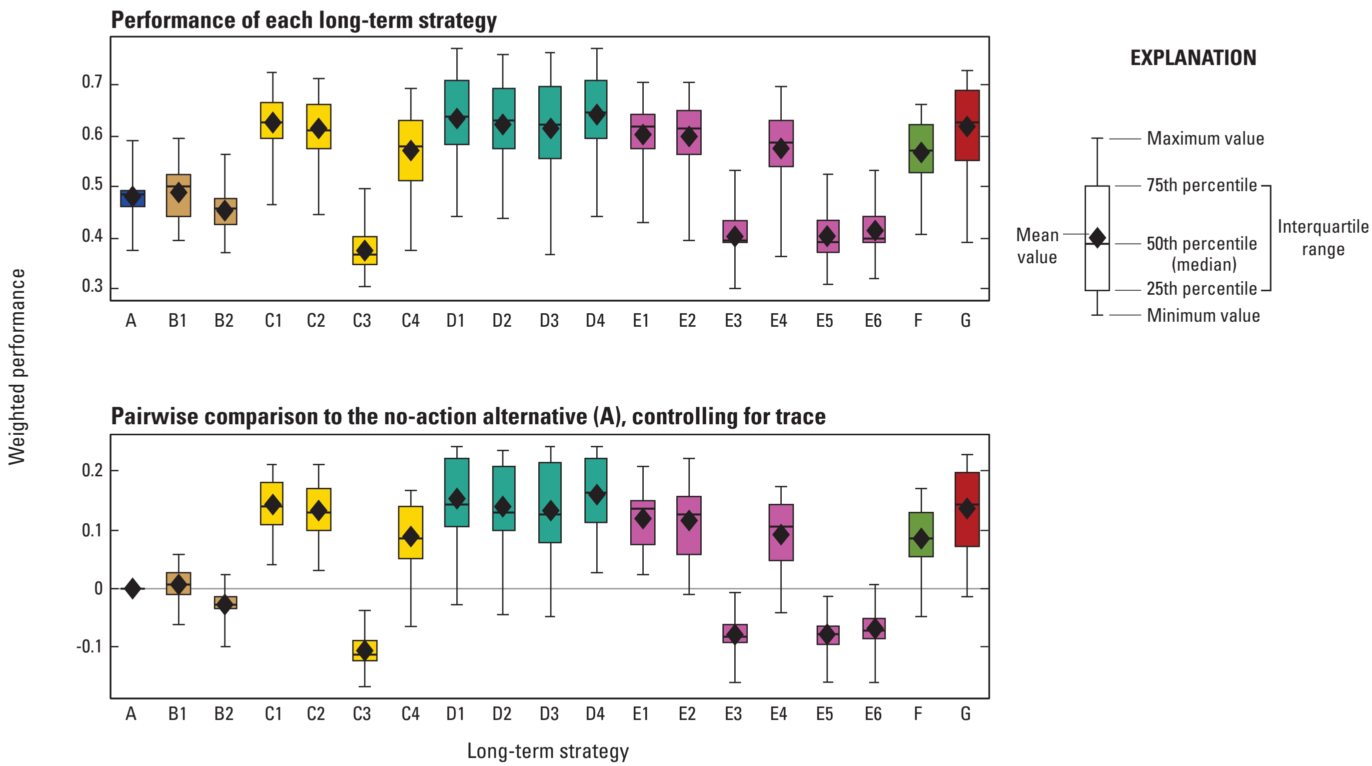

Figure 27. Joint-lead agency weighted performance across 18 metrics forecast for 19 long-term strategies using the climate-change weighting of hydrological traces.

keep in mind that the traces that were run through the modeling did not include plausible scenarios from the low end of the climate-change distribution.

9 Discussion

The analysis in this report is meant to add to the analysis in the LTEMP EIS itself. For those resource goals that could be evaluated with quantitative performance metrics, the tools of decision analysis allowed us to integrate the consequence analysis with the value judgments of stakeholders to formally evaluate the tradeoffs among the resource goals and to examine the influence of uncertainty on the performance of the long-term strategies. It is important to note, however, that not all the resource goals of importance could be evaluated quantitatively. The LTEMP EIS contains a narrative analysis of a greater number of resource goals than were included in the decision analysis, and this greater set of goals may be influential for the stakeholders and joint-lead agencies.

9.1 Evaluation of Alternatives

The alternatives examined in the LTEMP EIS and their long-term strategies differed in performance across the metrics considered. The full consequence table (table 7) shows strong tradeoffs: long-term strategies that perform well on any one performance metric may not perform well on others; thus, the choice of a preferred alternative will require the Secretary of Interior to weigh the importance of the various resource goals. The MCDA was designed as one way to provide input to the Secretary in her decision, by allowing the joint-lead agencies and stakeholders to express their interpretation of the importance of those resource goals and trace that interpretation through to the rankings of the alternatives. The best-performing long-term strategy did depend on the weights given to the performance metrics. Among the participating agencies, three alternatives rose to the top: Alternatives B, D, and G. Alternative B (especially long-term strategy B2) was favored by those agencies that emphasized the importance of the hydropower resource. Alternative G was the top- or second-ranked alternative for those agencies that emphasized restoration of natural processes, like beach building and native vegetation. For the remainder of the participating agencies, the analysis ranked Alternative D (especially long-term strategy D4) the highest. Alternative D was created after preliminary analysis revealed the strengths and weaknesses of the other alternatives and performs marginally better than the alternatives from which it was designed (C and E).

A number of other suggestions arise from the decision analysis regarding the long-term strategies. For most of the stakeholders, the benefits of HFEs seem to outweigh the costs, even in the face of uncertainty about their effects, at least as measured by the performance metrics included in this analysis. The other modifications (for example, TMFs, mechanical removal, low summer flows, and bug flows) produce equivocal results; their inclusion is neither convincingly demonstrated nor precluded by the decision analysis.

Several caveats are warranted in interpreting this report. First, the performance metrics evaluated represent only a subset of the resource goals that might be influenced by the alternatives. The LTEMP EIS provides a fuller discussion of other goals, and the stakeholders and decision makers will need to judge if the formal decision analysis represents a sufficient degree of completeness. Second, not all stakeholders with an interest in the LTEMP EIS chose to participate in the decision analysis; thus, the array of viewpoints represented (for example, fig. 22 and table 10) may not capture the full range or appropriate distribution of viewpoints. Third, even for those stakeholders that participated, it may be difficult to express a nuanced set of values through the swing-weighting process. The set of MCDA methods used assumes the resource goals can be traded against each other in a linear, additive, and independent fashion. In fact, the value a stakeholder places on one objective might depend on how well an alternative is also performing on another objective; such dependencies require other decision analysis methods that were not used here. Fourth, some of the performance metrics may not have directly captured the resource goals they were meant to represent. For instance, the SLI is a proxy for sediment deposition and retention but not necessarily directly correlated with it. Fifth, some of the performance metrics (like hydropower generation) were expressed on natural scales that can be readily understood, but some of the performance metrics were expressed on proxy scales (for example, SLI) or constructed scales (for example, fluctuation index) that are difficult to understand; this mixture of scales makes the swing-weighting judgments challenging.

The structuring of objectives and the development of appropriate performance metrics are critical steps in MCDA and require diligence to meet the assumptions of a linear, additive value model (the form of MCDA used in this analysis). One of the concerns is the possible inclusion of means objectives, leading to possible double counting in the weighting process; for example, there was considerable discussion about the inclusion of the RBT emigration rate (performance metric 4)—was it fundamental or merely a means to conserving native fish populations? For some stakeholders, it was fundamental as an expression of the conservation of natural processes. But for other stakeholders, weight may have been placed on this objective as an expression of the effect of trout on native fish, thus, leading to possible double counting. Another concern is the possible inclusion of preferentially dependent objectives; for example, were RBT catch rate (performance metric 3) and abundance of high-quality RBT (performance metric 5) treated as independent in the swing-weighting exercise, or did the participants assume that if you had one, you would have the other and so assign weight based on simultaneous achievement? The two-stage swing-weighting may have helped reduce this concern, but with the large number of performance metrics being evaluated, cognitive mistakes in the swing-weighting exercise could still have happened. When applying decision theory to real problems, with all their subtleties and complexities, it is difficult to achieve perfect adherence to the assumptions of the analysis, but diligence toward those assumptions is needed.

All these caveats are fair, and the interpretation of the results should account for them. But the analysis also represents an effort to use the best available science to explicitly examine the ranking of alternatives as influenced by an analysis of consequences and the relative values placed on the resource goals.

9.2 Motivation for Adaptive Management

The purpose of doing the EVPI calculation was to understand the importance of resolving uncertainty (and the relative importance of resolving the different sources of uncertainty) before beginning experimental design. This puts the focus of uncertainty on its value to the decision maker, rather than its value as a point of scientific discovery. Although much has been written about the many scientific uncertainties about how the Colorado River ecosystem responds to management, less has been documented about how resolution of those uncertainties would explicitly affect and improve management decisions. The value of information analysis identifies the following: what long-term management alternative is best assuming each of the competing hypotheses, what long-term management alternative is best in the face of uncertainty (if uncertainty cannot be resolved), how much long-term management can improve through resolution of uncertainty, and which components of uncertainty contribute most to the value of information. Of course, what constitutes “best” depends on how the decision maker values the multiple resource goals within their statutory framework, so the analysis includes the sensitivity of the value of information to the weights on the objectives.

The results presented in this report (including the MCDA and EVPI analyses) provide valuable information for the construction of an experimental or adaptive design that is targeted to the most importance sources of uncertainty and has the best chance of resolving that uncertainty. The design of an adaptive strategy needs to consider three important elements: the value of the information being sought, the power of any experimental or adaptive design to resolve that uncertainty, and the short-term costs to the resource goals of pursuing the reduction of uncertainty. Although there are optimization algorithms to derive adaptive strategies taking these factors into account, for example, active adaptive stochastic dynamic programming (Williams, 1996), such tools are difficult to use in such a complex system.

Interestingly, the EVPI analysis suggests that there is not much advantage in an experimental approach because the resolution of the uncertainties articulated is not expected to alter the choice of long-term strategy. This suggestion, however, hinges on the assumption that the uncertainties examined are a complete set. What about the "unknown unknowns," the uncertainties that we cannot yet articulate, but which we might nevertheless discover? We cannot analyze their importance, without being able to estimate their effect, and we also cannot design a monitoring system to detect them reliably. But, ongoing monitoring of the important resource goals, coupled with experimental implementation of the novel elements of any chosen alternative, is likely to reveal any surprises that would affect the achievement of the resource goals.

9.3 Decision Analysis and the National Environmental Policy Act

A typical analysis under the NEPA looks quite a bit like a formal decision analysis: resource goals (objectives) are articulated, alternatives are designed and described, and alternatives are evaluated against the individual resources of concern. These analyses are often qualitative, but a mix of qualitative and quantitative tools is also common. What is often missing from such analyses is a formal way to synthesize the results across the resources of concern. To the extent that NEPA is meant as a way to disclose to the public the environmental effects of the considered actions, such a synthesis is not needed. What decision analysis adds is a formal, quantitative way for the decision maker to consider and express the relative importance of the various resource goals in choosing a preferred alternative. In our view, then, decision analysis provides a useful companion to the analyses completed in an EIS.

The use of formal decision analysis in the context of a NEPA process was unfamiliar to a number of the Cooperating Agencies and other stakeholders, and several noted their discomfort with its use in comments to the joint-lead agencies. One-half of those stakeholders invited to participate in the swing-weighting exercise chose not to do so (table 9). They cited a number of concerns: skepticism that all the resources could be evaluated quantitatively, distrust of the methods of MCDA generally, a preference for providing input in a format they felt comfortable with, and a desire not to be forced to make an explicit value judgment on all the resource goals. Underlying the concerns was a stated fear that the decision analysis methods would be used to make the decision rather than just support an understanding of the alternatives. At all points, the joint-lead agencies and DOI leadership assured the stakeholders that the decision analysis was an effort to explore the performance of the proposed alternatives as deeply as possible with quantitative tools but was being used as only one of many sources of input in the transparent, deliberative process sought under NEPA. The effective use of decision analysis tools in the context of future NEPA processes will benefit from the insights of additional case studies, and from improved communication and training with regard to the theory, practice, justification, and benefits of decision analysis.

10 Summary

This report describes a formal decision analysis led by the U.S. Geological Survey, in cooperation with the Bureau of Reclamation, National Park Service, and Argonne National Laboratory, to support the development and evaluation of alternatives for the Glen Canyon Dam Long-Term Experimental and Management Plan. A set of 12 resource goals formed the basis of this evaluation, with 18 performance metrics used to provide quantitative measures of the resource goals. A total of 19 long-term strategies associated with 7 alternatives were evaluated against the performance metrics using a series of linked simulation models. Stakeholder input was elicited using the swing-weighting method, and this input was coupled with the quantitative evaluation of the alternatives in a multicriteria decision analysis. For 10 out of 13 stakeholder weightings presented, Alternative D (in particular, long-term strategy D4) outperformed the other alternatives. For the remaining stakeholder weightings, Alternatives B and G were the top performers. These rankings were robust to the uncertainties examined; the value of resolving uncertainty was never greater than 7.5 percent for any performance metric, and never greater than 2.5 percent for any stakeholder-weighted performance. This analysis is not a substitute for the full qualitative analysis found in the Long-Term Experimental and Management Plan Environmental Impact Statement, but does provide a transparent way to synthesize the analyses that could be quantified.

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12 Appendix 1. Disclaimers

In preparatory discussions with the Adaptive Management Working Group (AMWG) stakeholders and Cooperating Agencies, the joint-lead agencies and U.S. Department of the Interior (DOI) wanted to be clear about the role of the decision analysis in the Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS) process. The following disclaimer is to be included in the EIS when describing the use of formal decision analysis. (Note that during the discussions with the stakeholders, the term "structured decision analysis" was used as shorthand for the process being used. In this report, we follow the common practice in the literature and simply refer to the process as "decision analysis." The disclaimers below are reproduced verbatim, and so retain the use of the term "structured decision analysis"). A number of the participating stakeholders added disclaimers of their own when they submitted their swing-weighing results; these are also included below.

12.1 Standard Disclaimer

In an effort to provide multiple opportunities for interested stakeholders to provide input in the LTEMP process, the National Park Service (NPS) and Bureau of Reclamation (hereinafter referred to as "Reclamation") have decided to incorporate facilitated structured decision analysis (SDA) into the LTEMP EIS process. The SDA has been used previously for one aspect of the Glen Canyon Dam Adaptive Management Program (GCDAMP), the "Environmental Assessment for Non-Native Fish Control below Glen Canyon Dam." The use of SDA in the LTEMP process is not required by the National Environmental Policy Act (NEPA), nor does it replace the NEPA impact analysis.

Participation in the SDA process is a voluntary opportunity for stakeholder input. The NPS and Reclamation recognize that any input provided during the SDA effort does not replace the need and opportunities for formal public comment that are required steps in the NEPA process. Such formal comments on the Draft and Final EISs will be regarded as the formal and official positions of any commenting entity.

The use of SDA is an effort to cast a complex decision setting into a transparent, comprehensive but compressed form to help the decision makers and stakeholders see the essential elements; it may not, however, capture all nuances perfectly. The NPS and Reclamation recognize that the metrics for identified resource goals in the SDA do not necessarily reflect consensus or agreement among participants; moreover, the swing-weighting values to be applied to the metrics for identified resource goals may not reflect the broader policies or the importance of issues for any participant or agency. Stakeholders have had and will have formal opportunities to express their values through standard steps in the NEPA process, especially the submission of alternatives and public comments; for some stakeholders, these steps may allow them more flexibility to express their values in a familiar form than the decision analysis.

For these and other reasons, neither the co-leads nor the swing-weighting participants are bound by any outcomes or results of the SDA process. The NPS and Reclamation will use the results of the SDA process as one of multiple sources of information to inform the NEPA process, but the SDA process itself will not be used in isolation from other input to select the preferred alternative; rather, the NPS and Reclamation will choose a preferred alternative based on their statutory missions and responsibilities, giving consideration to legal, economic, environmental, technical, and other factors, as well as formal public input.

12.2 Arizona Department of Water Resources Disclaimer

The Arizona Department of Water Resources (ADWR) understands that the use of SDA in the LTEMP process is not required by NEPA, nor does it replace the NEPA impact analysis; furthermore, the ADWR recognizes that any input provided during the SDA effort does not replace the need and opportunity for formal public comment that are required steps in the NEPA process. Such formal comments on the Draft and Final EISs, in addition to the attached swing-weight exercise input, will be regarded as the formal and official positions of the ADWR.

The ADWR further recognizes that the swing-weighting values that have been applied to the metrics for identified resource goals do not reflect the broader policies or the importance of issues for the State of Arizona. The importance and priority of the values of ADWR are more accurately reflected within the "Resource Targeted Condition-Dependent" alternative, being necessarily incorporated during alternative creation. For these and other reasons, the ADWR is not bound by any outcomes or results of the SDA process.

Moreover, ADWR understands that the NPS and Reclamation will not solely rely on the results of the SDA process to select a preferred alternative; rather, the NPS and Reclamation will choose a preferred alternative based on their statutory missions and responsibilities, giving consideration to legal, economic, environmental, technical formal public input and other factors.

12.3 Arizona Game and Fish Department Disclaimer

The Arizona Game and Fish Department (AGFD) understands that the use of SDA in the LTEMP process is not required by NEPA, nor does it replace the NEPA impact analysis; furthermore, the AGFD recognizes that any input provided during the SDA effort does not replace the need and opportunity for formal public comment that are required steps in the NEPA process. Such formal comments on the Draft and Final EISs will be regarded as the formal and official positions of the AGFD, in addition to the attached swing-weight exercise.

The AGFD further submits that the swing-weighting values that we have provided for the metrics for identified resource goals do not reflect the broader policies or the importance of issues for the State of Arizona as a whole; rather, they represent AGFD values as they relate to our specific statutory authority and mission. For these and other reasons, the AGFD is not bound by any outcomes or results of the SDA process.

The AGFD understands and expects that the NPS and Reclamation will not solely rely on the results of the SDA process to select a preferred alternative; rather, the NPS and Reclamation will choose a preferred alternative based on their statutory missions and responsibilities, giving consideration to legal, economic, environmental, technical, formal public input and other factors.

12.4 Salt River Project Explanatory Letter

The Salt River Project (SRP) submits the attached swing-weighting exercise response under the following conditions:

- that this letter entitled "SRP's SDA Evaluation" remain attached to the SRP swing-weighting response table, and
- that the information submitted herein is not authorized for use, or attribution, beyond the purposes of this specific exercise in the current LTEMP EIS process.

1. *Hydropower (100).*—The SRP believes that the hydropower resource goal is the only one that represents both societal and environmental benefits. Greater quantities of hydropower provide cost effective service to people who value electricity to support many aspects of their lives. Greater quantities of this renewable, carbon-free resource also serve to avoid emissions and water use by other electric generating facilities. In the initial round of swing weighting, energy and capacity are valued equally.
    1. The energy metric does not appear to function in a consistent, intuitive manner; for example, a more flexible alternative with more energy production in higher-value months sometimes performs worse than a less flexible alternative with less energy production in higher-value months.
    2. While the capacity metric currently looks at July, SRP's peak demand requirement most often occurs in August, and our understanding from the Western Area Power Administration (WAPA) is that August is a better choice for peak planning purposes from their perspective as well. The SRP believes that utilizing August for peak demand planning would produce more credible capacity metric results.
2. *Humpback Chub (75).*—The SRP recognizes the environmental significance of the endangered humpback chub (HBC) (*Gila cypha*). The SRP supports the assembly of scientific evidence that establishes clear cause and effect relationships between flow regimes and a recovery of this endangered species. The "Number of Adult Humpback Chub" metric looks specifically at chub population, so the SRP places more emphasis on this metric than the "Temperature Suitability Index" metric.
3. *Archaeological and Cultural Resources (60).*—The Archeological and Cultural Resources goal represents an important societal benefit that the SRP supports; furthermore, SRP's perception is that, as presently crafted, the Archeological and Cultural Resources goal contains a more accurate representation of tribal interests than the "Tribal" resource goal. The SRP supports alternatives that science shows will preserve these resources.
    1. At the April Workshop, it was mentioned that the Time-off-river index was the issue that could lead to degradation of archeological and cultural resources; thus, this metric was scored highest.
    2. There has been some discussion about the wind transport of sediment index (WTSI). Specifically, some LTEMP representatives indicated that they would not want architectural and cultural sites buried by sand. This metric was, therefore, scored less highly.
    3. Based on new data from high-flow experiments (HFEs), it is unclear how HFEs and sediment affect downstream architectural and cultural sites. Because there are some winners and some losers, it is uncertain how the single "GLCA flow effects of historic properties (Ninemile)" metric can be representative of all sites; for example, science shows that HFEs will not increase sand bars before river mile (RM) 30 since there is no silt inflow. Even below RM 30, some sandbars cannot be built up to previous levels because even the maximum output of GCD cannot push sand high enough; thus, the SRP is not weighing this option as heavily as the others.
4. *Trout Fishery (40).*—The SRP recognizes the recreational value of the trout fishery and weighs the benefits against the environmental dangers of trout migration on downstream resources in the Grand Canyon ecosystem.

Since science appears to show that trout stay relatively close to Lees Ferry, SRP would not weigh "Lees Ferry trout emigration estimate" metric as heavily as if trout emigrated more through the canyon. As long as trout are not affecting downstream resources, the other metrics are also important to the trout fishery; thus, the "Angler Catch Rate Index" and "Number of trout > 16 inches total length" sublevel metrics are scored lower than the emigration metric but are still valued.

5. *Recreation (20).*—The SRP recognizes the societal value of recreation and believes Glen and Grand Canyons should be enjoyed by anyone who visits. While most visitors who visit the Grand Canyon do not raft down the canyon, the subset of people who do so should be considered.

    1. The "GRCA camping area index" is an important metric because people need safe areas to camp for the night. This is the highest rated metric.

    2. The fluctuation index is less highly rated because it does not take the time of day of the fluctuation into account.

    3. The GLCA rafting use index does not appear to have enough swing from low to high values to be rated highly. The swing of 600 people per year that could not take a trip down the river is not the same scale of an impact as a 1,000 fish population increase for HBC or a $9 million per year increase in hydropower energy value.

6. *Riparian Vegetation (20).*—The SRP recognizes the effect of riparian vegetation on the ecosystem of the Grand Canyon and believes it is has valuable environmental impacts. The aggregation of all metrics into this single metric hides some of the complexities; for example, CDAS and SASF perform worst for native/nonnative ratio but best for arrowweed. These are not able to be considered separately, which makes specific value judgments difficult.

7. *Sediment (0).*—The SRP observes that the effects of sediment are accounted for in the HBC, Archaeological & Cultural, Recreation, and Riparian Vegetation metrics. The SRP's perception is that sediment is a means to an end. We believe that a separate sediment metric does not make sense in the same manner that a separate temperature or HFE metric does not make sense.

8. *Tribal (0).*—The SRP believes that tribal interests should be recognized as a valued dimension of the LTEMP EIS process; however, as presented assembled and stated, the Tribal Resource goal does not appear to effectively represent tribal interests. The results for "Change in Marsh Vegetation" were questioned at the April Workshop and were not changed before this swing weighting. Trout should only be removed when they are endangering HBC, and the decision of how to remove them would preferably comply with tribal interests.

12.5 Utah Associated Municipal Power Systems Explanatory Letter

Utah Associated Municipal Power Systems (UAMPS) representing over 30 UAMPS members contracting for power generating output of Glen Canyon Dam is pleased to submit our response to the swing-weight exercise related to the LTEMP EIS process. The UAMPS is both an LTEMP EIS Cooperating Agency, a member of Glen Canyon Dam Adaptive Management Workgroup, and has been involved with most activities related to the operation of Glen Canyon Dam since environmental studies began in the mid-1980s. The UAMPS is grateful for the opportunity to participate in the EIS process as a member of the AMWG and as a Cooperating Agency contributor. We are appreciative of the great amount of work performed by both Federal government employees and contractors performing studies and assembling vast amounts of reporting documents, as well of those interested parties who have been following this LTEMP process.

We continue to be concerned with the valuation of the electric generation from Glen Canyon Dam and the reduction of power capacity and see this loss will be required to be replaced by resources using fossil fuels emitting carbon dioxide, which create other environmental problems and considerations. Thus far, we have not seen any expression of impacts of capacity switching except for some costs of capacity data for natural gas generation. In that regard, we wish to support the comment submitted by the Colorado River Energy Distributors Association (CREDA) that the cost estimates for natural gas combined-cycle generation in today's costs included in the performance metrics are way undervalued and should be corrected. We also hope additional cost analysis will eventually be included to address the lost power generating flexibility at Glen Canyon Dam needed for the western power grid. The flexibility provided by this hydropower is not free and will need to be made-up by some other power generating resource paid for by all utilities connected to the WECC power grid. Thus far, this loss of generating flexibly and the environmental impacts resulting from the shift to fossil fuels has only been casually addressed. We see the environmental objectives in this EIS seem to have priority over the far reaching climate change impacts that the electric industry in the west faces more and more as it struggles meet electric demands.

12.6 Colorado River Energy Distributors Association Submittal Letter

This letter [dated April 18, 2014] is an integral part of CREDA's SDA swing-weighting exercise submittal. CREDA members are all non-profit wholesale customers of the Salt

Lake City Area Integrated Projects (SLCA/IP) firm electric and transmission resources, of which Glen Canyon Dams is the largest generating facility. Although all members are non-profit entities, CREDA membership is diverse. Therefore, responses provided on the attached exercise cannot be ascribed to any individual CREDA member, as individual members did not have the ability to participate in the 5 days of workshop nor complete the exercise individually. Further, the responses are submitted with the understanding that the results will be reported with participant attribution and included in the draft/final Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS). Further, it is not clear to CREDA in what other forums this submittal is intended for use or attribution. Given those assumptions, CREDA submits its SDA swing-weighting response under the conditions that a) this letter shall remain attached to the SDA swing-weighting response table, and 2) the information submitted herein is not authorized for use or attribution beyond purposes of this specific exercise in the LTEMP EIS processes and documents.

SDA AND LTEMP: Having participate fully in the August and March-April SDA workshops, it has become clear to CREDA this this process may not lend itself readily to a system and resources as complex and interdependent as we see in the resources of interest in the LTEMP. As the performance metrics and models have been developed and evolved, CREDA still has concerns about some of the underlying Resource Goals, and their inconsistency with the AMWG-approved Desired Future Conditions. Although many comments and concerns have been expressed on some of the Goals in various forums and through various medium, the Goals have remained unchanged since LTEMP scoping, As we were advised on April 1, if a participant still has concerns with a Resource Goal, or if the participant believes the elements of a metric are contradictory, inappropriately "linked" to a Resource Goal, or a create a potential legal or policy conflict, the participant should value the metric with a very low or 0 value. We appreciate the time and effort involved in developing and facilitating the SDA process, but suggest that it may be more applicable and useful for either determining stakeholder values of individual attributes of a resource, or analyzing a reduced number of alternatives (particularly when many of the LTEMP alternatives were "split up" for this exercise). We commend the stakeholders who devoted a significant amount of time and effort to the August 2013 and this year's process.

SDA, HYDROPOWER ANALYSIS AND LTEMP: As you are aware, CREDA is participating in this process as a member of the Glen Canyon Dam Adaptive Management Work Group (AMWG), representing "contractors for the purchase of Federal power produced at Glen Canyon Dam". As such representative, CREDA's submittal of the Balanced Resource Alternative represents the value we ascribe to the hydropower resource, notwithstanding we have some outstanding questions about how this alternative was ultimately modeled for the SDA process. Participants in the April workshop were advised that the hydropower performance metric was incomplete, and that a key component of the metric, capacity, had to be developed by Argonne in an inordinately short period of time (April 1–8), further, that the "ratepayer analysis" portion of the hydropower analysis was noted as "still under discussion" in the Performance Metrics document provided to the workshop participants. CREDA offers detailed comment herein on the energy, capacity and ratepayer analysis components of the hydropower resource, as we were invited to do as soon as possible after the April 1 workshop. We understand and expect that the electric resource flexibility component of the metric will be assessed as part of the draft/full EIS process, and that air quality impacts, such as carbon offsets will also be a part of the overall hydropower analysis. We offer the following comments and suggestions for use in assessing hydropower resources going forward in the LTEMP process.

ENERGY: The information provided to the SDA workshop participants on April 1 has results that are unintuitive. For example, one can compare RTCD4 with BR1. Both have Fall HFEs. BR1 has an average output of 14,500 cfs during July and August, while RTCD4 has an average output of 12,000 cfs and 11,000 cfs respectively. Furthermore, BR1 has an average fluctuation range that is 140% of MLFF, while RTCD4 has an average fluctuation range that is 114% of MLFF. Based on common knowledge, BR1 should perform better for energy than RTCD4. However, based on modeling results, RTCD4 performed better. This example, along with others discussed during the April 4 meeting, call the energy results into question. *We urge the LTEMP co-leads to utilize the expertise of the cooperating agency utility experts in energy analysis. We would also like to see more detailed energy results, as was agreed in the April 4 conference call.*

CAPACITY: The information provided to the SDA workshop participants on April 10 indicates that the capacity metric uses July as its peak month. CREDA reaffirms its suggestion on March 31 that August be used as the peak month to reflect actual utility peak demand experience, both past and as projected for the period of the LTEMP EIS. Also included in the April 10 information is a capacity value of $65,000/MW-yr to be used in the swing-weighting process, based upon the following factors:

- 620-MW natural gas combined cycle plant
- Capital cost of $917/kW
- Fixed operation and maintenance cost of $13.17/kW
- 30-year lifetime
- Discount rate of 3.8%

CREDA believes, based on discussion with its utility members who are also cooperating agencies in the LTEMP, that a more accurate estimate of the capacity value for a large, natural gas combined cycle facility is in the range of $82,000/MW-yr–$132,000/MW-yr.

As a consulting service to the electric utility industry, the Electric Power Research Institute (EPRI) regularly prepares estimates of the costs associated with developing various types of energy resources, including gas-fired combined cycle facilities. EPRI's publicly available Generation Technology Options Report (published 2/19/2013) can be accessed at the linked site. EPRI information provided below can be found in Table 1-2 of their report.

Having worked with EPRI for a number of years with respect to resource characteristics and cost information for various electric resource technologies, a CREDA member's experience suggests that EPRI's valuations often do not fully account for the generally higher elevations and harsher ambient conditions that exist in CREDA member service regions relative to the assumptions used in EPRI's technology assessment efforts. Consequently, the CREDA member's internal cost estimates are higher. A comparison of key factors is provided below.

In summary, CREDA believes that the currently proposed values for LTEMP capacity valuation result in an understatement of Glen Canyon hydropower capacity value on the basis of a credible, publicly available, industry standard source for such information (EPRI) as well as on the basis of utility specific information and experience. *We urge the LTEMP co-leads to utilize the expertise of the cooperating agency utility experts in capacity analysis.*

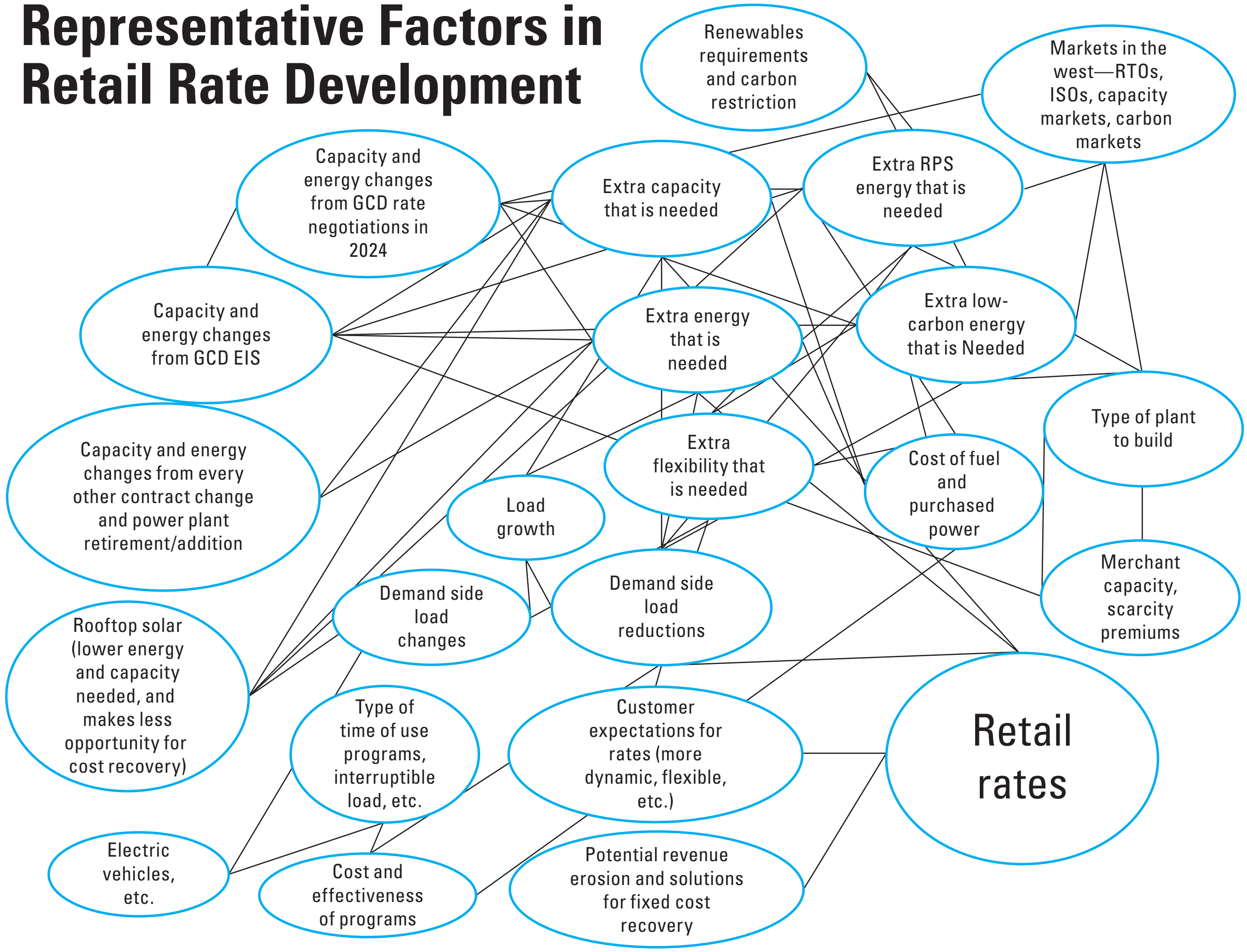
RATEPAYER ANALYSIS: As was recently communicated to Ass't. Secretary Castle, CREDA and its electric utility members believe that this analysis must be based on and reflect impacts to the product/resource produced through the operation of Glen Canyon Dam, which is *wholesale* electric power and energy. On 4/1/14, we again objected to an attempt to develop and include a *retail* rate analysis, which is not required by NEPA, and which will likely be incorrect and misleading because it will not be possible to obtain sufficient and credible data given the time constraints and budget dollars associated with the LTEMP process. The chart below provides some perspective about the complexities involved in electric utility retail rate development. *Consistent with the scope of federal agency responsibility, to the extent any ratepayer analysis is required (which we don't believe is the case under NEPA), we urge the LTEMP co-leads to focus on the wholesale level, and consider utilizing cooperating agency utility expertise.*

Finally, CREDA recognizes the time and effort spent by all the SDA participants and believes that a key outcome from the workshops and exercises is the opportunity afforded the AMWG stakeholders, LTEMP co-leads, Argonne National Labs and GCMRC personnel and contractors to learn more about and appreciate the complexities and interdependencies of the resources addressed through the Adaptive Management Program, as well as the challenges faced by the Secretary of the Interior in balancing the resources associated with the operation of Glen Canyon Dam. It has also become clear through the model development and results supporting the SDA process that the resources of concern are "performing well" under the current operational and management parameters. The LTEMP co-lead and cooperating agencies should strongly consider this information.

	Factor	LTEMP	EPRI	CREDA
1	Capital Cost	$917/kw	$1,025/kw–1,325/kw	$1,130/kw–$1,426/kw
2	Fixed O&M Cost	$13.17/kw-yr	$15/kw-yr	$23/kw-yr–$25/kw-yr
3	Discount Rate (1)	3.8%	5%	Higher than 5%
4	Resulting Capacity Cost (2)	$65,000/MW-yr	$82,000/MW-yr–$101,000/MW-yr	$108,000/MW-yr–$132,000/MW-yr

(1) The discount rates of CREDA members are proprietary and confidential information.
(2) Lower cost represents wet cooling, higher cost represents dry cooling.

Representative Factors in Retail Rate Development



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APPENDIX D:

HYDROLOGY TECHNICAL INFORMATION AND ANALYSIS

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APPENDIX D:

HYDROLOGY TECHNICAL INFORMATION AND ANALYSIS

D.1 ANALYSIS METHODS

The Colorado River Simulation System (CRSS) is the modeling tool used to assess the effects of the Long-term Experimental and Management Plan (LTEMP) alternatives on water resources and to provide relevant information to other models used to assess other resources. This section provides a background on CRSS, all relevant modeling assumptions used in CRSS, and a description of any changes that were made to CRSS, specifically for the LTEMP modeling.

D.1.1 Background

The CRSS, the Bureau of Reclamation's (Reclamation's) long-term planning model that covers the Colorado River Basin (Basin) from the natural inflow points in the Upper Basin (see Figure D-3) to Imperial Dam, was the first model used in LTEMP Draft Environmental Impact Statement (DEIS) analysis process. CRSS simulates future system conditions based on different hydrologic inflow scenarios and assumed reservoir operations for the evaluation period (2013–2033). The model framework used for this process is a commercial river modeling software called RiverWare™ (Zagona et al. 2001), a generalized river basin modeling software package developed by the University of Colorado through a cooperative arrangement with Reclamation and the Tennessee Valley Authority. CRSS was originally developed by Reclamation in the early 1970s and was implemented in RiverWare™ in 1996.

CRSS simulates the operation of the major reservoirs on the Colorado River and provides information regarding the projected future state of the system on a monthly basis in terms of output variables including the amount of water in storage, reservoir elevations, releases from the dams, the amount of water flowing at various points throughout the system, and the diversions to and return flows from the water users throughout the system. The basis of the simulation is a mass balance (or water budget) calculation that accounts for water entering the system, water leaving the system (e.g., from consumptive use of water, trans-basin diversions, evaporation), and water moving through the system (i.e., either stored in reservoirs or flowing in river reaches). The model was used to project the future conditions of the Colorado River system on a monthly time-step for the period 2013 through 2033.

The input data for the model includes monthly natural inflows,[1] various physical process parameters such as the evaporation rates for each reservoir, initial reservoir conditions on January 1, 2013, and the future diversion and depletion schedules for entities in the Basin States and for the United Mexican States (Mexico). These future schedules were based on the Current

[1] Calculated as gaged flow corrected for the effects of upstream reservoirs and depletions. Natural flow data and supporting documentation are available at http://www.usbr.gov/lc/region/g4000/NaturalFlow/index.html.

Projected demand scenario (Schedule A) from the Colorado River Basin Water Supply and Demand Study (Basin Study [Reclamation 2012b]).

The rules of operation of the Colorado River mainstream reservoirs including Lake Powell and Lake Mead are also provided as input to the model. This set of operating rules describes how water is released and delivered under various hydrologic conditions and aims to reflect actual operations. However, limitations inherently exist in the model's ability to reflect actual operations, particularly when responding to changing hydrological conditions and other operational constraints such as dam maintenance.

The future hydrology used as input to the model consisted of samples taken from the historical record of natural flow in the river system over the 105-year period from 1906 through 2010 and the "Downscaled GCM Projected" water supply scenario from the Basin Study (Reclamation 2012a). Each sequence is input as natural flow at 29 individual inflow points (or nodes) on the system. The future hydrology is merely a projection of what future conditions might be based upon the 105-year record, and is not a prediction of the likelihood of these future hydrologic conditions occurring.

The following sections describe the CRSS modeling assumptions and configuration associated with the modeling undertaken for the LTEMP DEIS process. The version of CRSS used for the LTEMP modeling started from the version of CRSS used for the Basin Study and was updated with more recent initial conditions and other changes necessary to reflect the different alternatives, as described below.

D.1.2 Initial Conditions

The model was initialized with the observed 2012 end-of-calendar-year (EOCY) reservoir conditions shown in Table D-1.

D.1.3 Reservoir Operations

D.1.3.1 Upper Basin Reservoirs above Lake Powell

The Taylor Park, Fontenelle, and Starvation reservoirs are operated in accordance with their existing rule curves (Reclamation 2007), although Fontenelle's operating rules in CRSS have been updated since the 2007 Interim Guidelines (DOI 2007). Aspinall Unit operations do not reflect the *Record of Decision* (ROD) *for the Aspinall Unit Operations Final Environmental Impact Statement* (Reclamation 2012c) because the modeling for the LTEMP DEIS began before the latest Aspinall ROD could be reflected in CRSS. Instead, Aspinall Unit operations are also operated in accordance with their previous rule curves as documented in the *Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations of Lake Powell and Lake Mead Final Environmental Impact Statement* (2007 Interim Guidelines Final EIS [Reclamation 2007]).

TABLE D-1 Initial Reservoir Conditions (2012 Observed End-of-Calendar-Year Values)

Reservoir	Elevation (ft AMSL)	Storage (ac-ft)
Fontenelle	6,485.19	196,963
Flaming Gorge	6,020.63	3,001,912
Starvation	5,734.92	255,000
Taylor Park	9,301.09	56,647
Blue Mesa	7,452.65	327,537
Morrow Point	7,146.50	106,381
Crystal	6,749.11	15,830
Navajo	6,024.73	956,630
Powell	3,609.82	12,712,205
Mead	1,120.36	13,636,479
Mohave	638.30	1,572,110
Havasu	446.41	550,689

Navajo and Flaming Gorge operations reflect the recent RODs (Reclamation 2006a and 2006b, respectively). In general, both RODs contain downstream flow targets that the reservoirs attempt to meet according to the rules within the RODs. In summary, Flaming Gorge operations are governed by the April through July unregulated inflow into the reservoir, which determines which downstream flow targets should be met; for example, in a wet year (larger inflow into the reservoir), higher downstream flows are targeted. The flow targets are specified at the sub-monthly time step, which historically could not be reflected within CRSS. In order to capture the sub-monthly component of the flow targets, and thus Flaming Gorge's operations, the model was programmed to determine typical daily operations before summing to a monthly release (Butler 2011).

Similarly, Navajo's ROD contains multiple downstream flow targets, specified at sub-monthly time intervals. In this case, a September 30 storage target guides Navajo's operations. A release pattern is selected to bring Navajo as close as possible to the September 30 storage target while helping meet the downstream flow targets stated in the ROD (Butler 2011).

D.1.3.2 Lake Powell and Lake Mead

For 2013 through 2026, Lake Powell and Lake Mead would be operated according to the 2007 Interim Guidelines (DOI 2007). For modeling purposes, after the expiration of the 2007 Interim Guidelines in 2026, operations are assumed to conform to those specified in the No-Action Alternative from the 2007 Interim Guidelines Final EIS (Reclamation 2007). Both operations are briefly described below.

Lake Mead flood control procedures are in effect for the entire simulation period. In addition, if Lake Mead elevation falls below 1,000 feet above mean sea level (AMSL), deliveries to the Southern Nevada Water Authority (SNWA) are assumed to continue.

If Lake Mead is sufficiently low such that after the maximum shortage (per the 2007 Interim Guidelines or No-Action Alternative post 2026) is applied and water is still unavailable to meet the remaining deliveries, the remaining deliveries were shorted hydrologically with respect to their physical location on the river.

Operations during the Interim Guidelines (2013–2026)

Operations of Lake Powell and Lake Mead are coordinated as specified in the 2007 Interim Guidelines (DOI 2007). Figure D-1 summarizes the different operating tiers at both reservoirs. Based on rules programmed in the model, CRSS determines which tier Powell is operating in, and simulates releases consistent with the selected tier. Similarly, CRSS is configured to simulate normal, shortage, and surplus deliveries in the Lower Basin, consistent with the Interim Guidelines.

Operations after the Interim Guidelines Expire (2027–2033)

The operating rules reverted to the rules of the 2007 Interim Guidelines Final EIS No-Action Alternative for simulations starting in 2027 and continuing through 2033. The No-Action Alternative assumed the following for shortage, surplus, and coordinated operations. There was no intentionally created surplus (ICS) assumed in the No-Action Alternative, however; consistent with the 2007 Interim Guidelines, ICS deliveries would be permissible through 2036. See Appendix A of the 2007 Interim Guidelines Final EIS (Reclamation 2007) for additional details regarding the No-Action Alternative.

Three factors that affect Lake Powell's release are (1) the minimum objective release of 8.23 maf, (2) equalization, and (3) spill avoidance. For equalization to occur, the 602(a) storage requirement must be met.[2]

Stage 1 shortage is triggered to prevent Lake Mead from declining below 1,050 feet AMSL. Stage 1 shortages range in volume from approximately 350 to 500 kaf. If Lake Mead's elevation continues to decline, a Stage 2 shortage is imposed to keep Lake Mead above 1,000 feet AMSL. Stage 2 shortages can be up to 3.0 maf.

[2] See Appendix A of the 2007 Interim Guidelines Final EIS (Reclamation 2007) for the full 602(a) storage requirement computation.

Lake Powell		
Elevation (feet)	**Operation According to the Interim Guidelines**	**Live Storage (maf)[1]**
3,700	**Equalization Tier** Equalize, avoid spills or release 8.23 maf	**24.3**
3,636 - 3,666 (2008-2026)	**Upper Elevation Balancing Tier[3]** Release 8.23 maf; if Lake Mead < 1,075 feet, balance contents with a min/max release of 7.0 and 9.0 maf	**15.5 - 19.3** (2008-2026)
3,575	**Mid-Elevation Release Tier** Release 7.48 maf; if Lake Mead < 1,025 feet, release 8.23 maf	**9.5**
3,525	**Lower Elevation Balancing Tier** Balance contents with a min/max release of 7.0 and 9.5 maf	**5.9**
3,490		**4.0**
3,370		**0**

Lake Mead		
Elevation (feet)	**Operation According to the Interim Guidelines**	**Live Storage (maf)[1]**
1,220	**Flood Control Surplus or Quantified Surplus Condition** Deliver > 7.5 maf	**25.9**
1,200 (approx.)[2]	**Domestic Surplus or ICS Surplus Condition** Deliver > 7.5 maf	**22.9** (approx.)[2]
1,145	**Normal or ICS Surplus Condition** Deliver ≥ 7.5 maf	**15.9**
1,105		**11.9**
1,075	**Shortage Condition** Deliver 7.167[4] maf	**9.4**
1,050	**Shortage Condition** Deliver 7.083[5] maf	**7.5**
1,025	**Shortage Condition** Deliver 7.0[6] maf Further measures may be undertaken[7]	**5.8**
1,000		**4.3**
895		**0**

Diagram not to scale

[1] Acronym for million acre-feet

[2] This elevation is shown as approximate as it is determined each year by considering several factors including Lake Powell and Lake Mead storage, projected Upper Basin and Lower Basin demands, and an assumed inflow.

[3] Subject to April adjustments which may result in a release according to the Equalization Tier

[4] Of which 2.48 maf is apportioned to Arizona, 4.4 maf to California, and 0.287 maf to Nevada

[5] Of which 2.40 maf is apportioned to Arizona, 4.4 maf to California, and 0.283 maf to Nevada

[6] Of which 2.32 maf is apportioned to Arizona, 4.4 maf to California, and 0.280 maf to Nevada

[7] Whenever Lake Mead is below elevation 1,025 feet, the Secretary shall consider whether hydrologic conditions together with anticipated deliveries to the Lower Division States and Mexico is likely to cause the elevation at Lake Mead to fall below 1,000 feet. Such consideration, in consultation with the Basin States, may result in the undertaking of further measures, consistent with applicable Federal law.

FIGURE D-1 Operating Tiers as Specified by the 2007 Interim Guidelines (DOI 2007) for the Operations of Lake Powell and Lake Mead

Surplus determinations are per flood control surplus conditions or the 70R Strategy.[3]

Modeling Assumptions for Annual Releases Extending Beyond the Water Year

Modeling assumptions for equalization operations need to be performed for a full analysis of monthly and annual operations in this DEIS. These assumptions are for analytical purposes only and do not, and cannot, modify the Secretary's approach to operations of equalization releases that are made pursuant to the Colorado River Basin Project Act of 1968. Modeled equalization release volumes can be affected by the annual pattern of monthly volumes. Alternatives that have higher releases earlier in the water year are able to release more water in years when the maximum release through the powerplant becomes a potential limiting factor to equalizing within the water year, which is consistent with the objectives of the Law of the River. A limitation of the current modeling assumptions is that they cannot fully mimic or predict operator judgment or actions to achieve full equalization within the relevant timeframe. Reclamation will continue to operate Glen Canyon Dam to achieve equalization releases in a manner fully consistent with the Law of the River and in consultation with the Colorado River Basin States.

For LTEMP modeling, logic was added to CRSS to handle instances when Powell could not meet annual release requirements by the end of the water year. If the computed remaining release in September is greater than Powell's power plant capacity, then the volume above powerplant capacity necessary meet annual release requirements is released in the subsequent months. Releases, beginning in October, are increased above the normal release requirements (e.g., 600 kaf in an 8.23-maf release year of Alternative A, the no-action alternative) up to power plant capacity, for as many months as necessary to release the remaining equalization volume. The volume of annual releases extending beyond the water year and the frequency at which these releases would be necessary were reported as one of the calculated water resource metrics.

Setting Powell's Monthly Release Volumes

In order to more efficiently model the different alternatives being evaluated in the LTEMP DEIS, CRSS logic was modified to use an input release table, and to allow minimum release constraints to vary among alternatives. The tables include monthly release volumes for water year releases of 7.0, 7.48, 8.23, 9.0, 9.5, 10.5, 11.0, 12.0, 13.0, and 14.0 maf. In fixed release volume years (e.g., 8.23-maf release years), the monthly volumes used were directly from the input release tables presented in Section D.1.4, subject to other constraints such as ensuring Powell stays at a safe operating capacity. In years with computed release volumes

[3] Under the 70R Strategy, a surplus condition is based on the system space requirement at the beginning of each year. Based on the 70th percentile historical runoff, a normal 7.5-maf delivery to the Lower Division states, the Upper Basin scheduled use, and Lake Powell and Lake Mead volumes at the beginning of the year, the volume of water in excess of the system space requirement at the end of the year is estimated. If that volume is greater than zero, a surplus is declared. See Appendix A of the 2007 Interim Guidelines Final EIS (Reclamation 2007) for the full 70R computation.

(e.g., equalization releases), the necessary water year release volume is computed, and the monthly release is interpolated between the two closest water year releases. For example, if the equalization release is computed to be 12.5 maf, then the monthly release would be interpolated between the 12.0- and 13.0-maf monthly release volumes.

The minimum release constraints were also incorporated into CRSS because there are certain instances when the release from Powell may be computed to be less than the alternative's minimum release constraints. In these cases, the alternative's minimum release constraint is used, subject to the physical ability to release the water. Furthermore, the implementation of these constraints does not result in a modification of the annual release volume.

D.1.3.3 Lake Mohave and Lake Havasu

Lake Mohave and Lake Havasu are operated in accordance with their existing rule curves.

D.1.4 Representation of the Different Alternatives in CRSS

For each alternative, tables were developed that include the monthly release volumes that are modeled to occur under differing water year release volumes. In most cases, the volumes in the tables represent some desired aspect of the alternatives and were developed by proportionally scaling monthly volumes to the water year volume. However, in the minimum (7.0-maf) water release years and in the higher water release years, the proportionally scaled monthly volumes in the tables were sometimes adjusted up to meet minimum release constraints or down to powerplant capacity. All alternatives met the minimum release constraints and were within powerplant capacity in an 8.23-maf release year. However, in some months for some alternatives the proportionally scaled monthly volumes in the tables required adjustment to meet these constraints.

For example, the proportionally scaled monthly volumes in a 7.0-maf year were not always adequate to meet the minimum release requirement, as computed by the minimum hourly releases and ramping constraints. In these instances, the monthly release volume was set to the volume necessary to maintain minimum flow throughout the entire month. Similarly, in high-volume water release years, the proportionally scaled monthly volumes in the tables were sometimes greater than the physical capacity of Glen Canyon Powerplant. In these instances, the monthly release volume in the table was set to powerplant capacity, reallocating the excess into other months of the water year. The annual release volume was not affected by these modifications.

In addition to the physical capacity of the powerplant represented in the monthly tables input to CRSS, the maximum release capacity of Glen Canyon Dam (powerplant and bypass volume) can also affect modeled monthly release volumes, particularly in years with an annual release volume greater than 14.0 maf. The maximum release was modeled explicitly in CRSS as a function of reservoir head. Generally speaking, the maximum release was computed as

45,000 cfs; this flow was converted to a daily volume and then multiplied by the number of days in the month to determine the monthly maximum release volume. In months when the monthly release prescribed by the alternative was greater than the maximum capacity for the month, the monthly volume was capped at the physical capacity, and the remaining volume was released in the following month(s).

Monthly release volume can also be affected by high-flow experiments (HFEs). For HFEs that required more water than was already allocated for the given month of the HFE, water was reallocated from later months to ensure the water year release volume remained the same. For this DEIS, the monthly reallocation of water for HFEs was modeled as a post-process to the sand-budget model (i.e., after the model determined the magnitude and duration of the HFE). Reservoir mass balance was computed for the affected months and the resulting monthly releases and reservoir elevations were then passed to the hydropower model.

The monthly reallocation of releases to support a HFE does not affect the Lake Powell operating tier (and thus did not need to be explicitly modeled in CRSS). Operationally, the magnitude and duration of a HFE would be determined in either October–November or March–April. Because the Lake Powell annual operating tier is determined based on the August projection of the January 1 elevation, it is not yet known whether an HFE will take place that water year. Therefore, a modeled reallocation of water into November, for example, should not be considered when determining the annual operating tier because, operationally, this information would not be known until after the operating tier was already set.

Tables D-2 through D-11 include the monthly release tables used for all alternatives in CRSS, and Table D-12 summarizes the minimum release constraints used for each alternative. Figure D-2 shows the 8.23-maf release year pattern for all alternatives. In addition, the experimental components of LTEMP that are modeled in CRSS are also discussed.

Long-term strategies (various implementations of the seven LTEMP alternatives; described in Appendix C) that would not affect monthly or annual releases from Powell were not simulated in CRSS. These long-term strategies are labeled in the figures in this appendix as identical to another long-term strategy. For example, the only difference between long-term strategies D1 and D3 is that D1 includes trout management flows. Because trout management flows were not included in CRSS, results for D1 and D3 are identical and labeled as such in the water delivery results.

TABLE D-2 Monthly Release Volumes (in ac-ft) by Water Year Release for Alternative A

	Water Year Release (maf)									
Month	7	7.48	8.23	9	9.5	10.5	11	12	13	14
October	480,000	480,000	600,000	600,000	600,000	600,000	600,000	600,000	600,000	600,000
November	500,000	500,000	600,000	600,000	600,000	600,000	600,000	600,000	600,000	600,000
December	600,000	600,000	800,000	800,000	800,000	800,000	800,000	800,000	800,000	800,000
January	600,000	800,000	800,000	800,000	850,000	950,000	950,000	1,000,000	1,000,000	1,000,000
February	600,000	600,000	600,000	650,000	650,000	650,000	700,000	800,000	800,000	900,000
March	500,000	600,000	600,000	650,000	650,000	650,000	700,000	900,000	950,000	1,100,000
April	500,000	500,000	600,000	600,000	650,000	750,000	900,000	1,000,000	1,100,000	1,413,000
May	500,000	600,000	600,000	650,000	800,000	1,100,000	1,100,000	1,100,000	1,250,000	1,537,000
June	600,000	600,000	650,000	800,000	900,000	1,100,000	1,150,000	1,200,000	1,400,000	1,488,000
July	800,000	800,000	850,000	1,000,000	1,050,000	1,150,000	1,250,000	1,400,000	1,537,000	1,537,000
August	800,000	800,000	900,000	1,050,000	1,100,000	1,200,000	1,250,000	1,500,000	1,537,000	1,537,000
September	520,000	600,000	630,000	800,000	850,000	950,000	1,000,000	1,100,000	1,426,000	1,488,000

TABLE D-3 Monthly Release Volumes (in ac-ft) by Water Year Release for Alternative B

	Water Year Release (maf)									
Month	7	7.48	8.23	9	9.5	10.5	11	12	13	14
October	480,000	480,000	600,000	600,000	600,000	600,000	600,000	600,000	600,000	600,000
November	500,000	500,000	600,000	600,000	600,000	600,000	600,000	600,000	600,000	600,000
December	600,000	600,000	800,000	800,000	800,000	800,000	800,000	800,000	800,000	800,000
January	600,000	800,000	800,000	800,000	850,000	950,000	950,000	1,000,000	1,000,000	1,000,000
February	600,000	600,000	600,000	650,000	650,000	650,000	700,000	800,000	800,000	900,000
March	500,000	600,000	600,000	650,000	650,000	650,000	700,000	900,000	950,000	1,100,000
April	500,000	500,000	600,000	600,000	650,000	750,000	900,000	1,000,000	1,100,000	1,413,000
May	500,000	600,000	600,000	650,000	800,000	1,100,000	1,100,000	1,100,000	1,250,000	1,537,000
June	600,000	600,000	650,000	800,000	900,000	1,100,000	1,150,000	1,200,000	1,400,000	1,488,000
July	800,000	800,000	850,000	1,000,000	1,050,000	1,150,000	1,250,000	1,400,000	1,537,000	1,537,000
August	800,000	800,000	900,000	1,050,000	1,100,000	1,200,000	1,250,000	1,500,000	1,537,000	1,537,000
September	520,000	600,000	630,000	800,000	850,000	950,000	1,000,000	1,100,000	1,426,000	1,488,000

TABLE D-4 Monthly Release Volumes (in ac-ft) by Water Year Release for Alternative C

	Water Year Release (maf)									
Month	7	7.48	8.23	9	9.5	10.5	11	12	13	14
October	436,260	436,260	480,000	480,000	480,000	480,000	480,000	480,000	480,000	480,000
November	436,260	436,260	480,000	480,000	480,000	480,000	480,000	480,000	480,000	480,000
December	754,360	754,360	830,000	830,000	830,000	830,000	830,000	830,000	830,000	830,000
January	692,498	754,360	830,000	929,239	993,680	1,122,562	1,187,003	1,315,885	1,444,767	1,537,189
February	609,215	663,640	730,180	817,484	874,175	987,557	1,044,248	1,157,630	1,271,012	1,388,429
March	643,264	700,730	770,990	863,174	923,033	1,042,752	1,102,611	1,222,330	1,342,049	1,474,882
April	572,129	623,240	685,730	767,719	820,959	927,439	980,679	1,087,159	1,193,639	1,311,782
May	592,562	645,500	710,220	795,138	850,279	960,562	1,015,703	1,125,985	1,236,268	1,358,631
June	619,811	675,180	742,880	831,703	889,380	1,004,734	1,062,411	1,177,765	1,293,119	1,421,109
July	692,498	754,360	830,000	929,239	993,680	1,122,562	1,187,003	1,315,885	1,444,767	1,537,189
August	550,661	599,850	660,000	738,913	790,155	892,640	943,882	1,046,366	1,148,851	1,262,562
September	400,482	436,260	480,000	537,391	574,659	649,192	686,460	760,995	835,528	918,227

TABLE D-5 Monthly Release Volumes (in ac-ft) by Water Year Release for Alternative C with Low Summer Flows

	Water Year Release (maf)									
Month	7	7.48	8.23	9	9.5	10.5	11	12	13	14
October	436,260	436,260	480,000	480,000	480,000	480,000	480,000	480,000	480,000	480,000
November	436,260	436,260	480,000	480,000	480,000	480,000	480,000	480,000	480,000	480,000
December	754,360	754,360	830,000	830,000	830,000	830,000	830,000	830,000	830,000	830,000
January	692,498	754,360	830,000	929,239	993,680	1,122,562	1,187,003	1,315,885	1,444,767	1,537,189
February	609,215	663,640	730,180	817,484	874,175	987,557	1,044,248	1,157,630	1,271,012	1,388,429
March	643,264	700,730	770,990	863,174	923,033	1,042,752	1,102,611	1,222,330	1,342,049	1,474,882
April	708,598	771,899	849,296	950,842	1,016,781	1,148,660	1,214,599	1,346,477	1,478,355	1,487,603
May	733,905	799,467	879,628	984,801	1,053,095	1,189,683	1,257,977	1,394,566	1,531,154	1,537,189
June	767,648	836,224	920,070	1,030,079	1,101,513	1,244,381	1,315,815	1,458,684	1,488,000	1,487,603
July	410,410	447,074	491,901	550,715	588,906	665,288	703,479	779,862	894,506	1,110,981
August	410,410	447,074	491,901	550,715	588,906	665,288	703,479	779,862	894,506	1,110,981
September	397,172	432,652	476,034	532,951	569,911	643,829	680,789	754,704	865,651	1,075,143

TABLE D-6 Monthly Release Volumes (in ac-ft) by Water Year Release for Alternative D

	Water Year Release (maf)									
Month	7	7.48	8.23	9	9.5	10.5	11	12	13	14
October	480,000	480,000	642,583	642,583	642,583	642,583	642,583	642,583	642,583	642,583
November	500,000	500,000	641,532	641,532	641,532	641,532	641,532	641,532	641,532	641,532
December	600,000	600,000	715,885	715,885	715,885	715,885	715,885	715,885	715,885	715,885
January	664,609	723,467	763,000	858,351	919,662	1,042,283	1,103,594	1,226,216	1,348,837	1,471,459
February	587,262	639,271	675,000	758,457	812,632	920,983	975,159	1,083,510	1,191,860	1,300,211
March	620,206	675,132	713,000	801,004	858,219	972,648	1,029,863	1,144,292	1,258,721	1,373,150
April	552,170	601,070	635,000	713,134	764,072	865,949	916,887	1,018,763	1,120,640	1,222,516
May	571,506	622,119	657,000	738,108	790,830	896,274	948,996	1,054,440	1,159,884	1,265,328
June	598,005	650,965	688,000	772,331	827,497	937,830	992,997	1,103,330	1,213,663	1,323,996
July	651,718	709,434	749,000	841,702	901,823	1,022,067	1,082,188	1,202,431	1,322,674	1,442,918
August	652,434	710,214	750,000	842,627	902,814	1,023,190	1,083,377	1,203,753	1,324,128	1,444,503
September	522,090	568,328	600,000	674,286	722,451	818,776	866,939	963,265	1,059,593	1,155,919

TABLE D-7 Monthly Release Volumes (in ac-ft) by Water Year Release for Alternative D with Low Summer Flows

	Water Year Release (maf)									
Month	7	7.48	8.23	9	9.5	10.5	11	12	13	14
October	480,000	480,000	642,583	642,583	642,583	642,583	642,583	642,583	642,583	642,583
November	500,000	500,000	641,532	641,532	641,532	641,532	641,532	641,532	641,532	641,532
December	600,000	600,000	715,885	715,885	715,885	715,885	715,885	715,885	715,885	715,885
January	664,609	723,467	763,000	858,351	919,662	1,042,283	1,103,594	1,226,216	1,348,837	1,471,459
February	587,262	639,271	675,000	758,457	812,632	920,983	975,159	1,083,510	1,191,860	1,300,211
March	620,206	675,132	713,000	801,004	858,219	972,648	1,029,863	1,144,292	1,258,721	1,373,150
April	730,640	795,346	840,007	943,631	1,011,033	1,145,837	1,213,239	1,348,044	1,482,848	1,487,603
May	756,226	823,198	869,423	976,676	1,046,439	1,185,964	1,255,726	1,395,252	1,534,777	1,537,189
June	791,289	861,367	909,735	1,021,961	1,094,958	1,240,952	1,313,949	1,459,944	1,487,603	1,487,603
July	427,856	465,748	491,901	552,582	592,052	670,992	710,463	789,403	908,217	1,126,373
August	427,856	465,748	491,901	552,582	592,052	670,992	710,463	789,403	908,217	1,126,373
September	414,056	450,723	476,033	534,756	572,953	649,349	687,544	763,936	878,920	1,090,039

TABLE D-8 Monthly Release Volumes (in ac-ft) by Water Year Release for Alternative E

	Water Year Release (maf)									
Month	7	7.48	8.23	9	9.5	10.5	11	12	13	14
October	480,000	480,000	642,583	642,583	642,583	642,583	642,583	642,583	642,583	642,583
November	500,000	500,000	641,532	641,532	641,532	641,532	641,532	641,532	641,532	641,532
December	600,000	600,000	715,885	715,885	715,885	715,885	715,885	715,885	715,885	715,885
January	683,468	747,279	781,296	883,660	950,130	1,083,070	1,149,540	1,282,480	1,415,420	1,548,360
February	604,808	661,275	691,377	781,960	840,780	958,420	1,017,240	1,134,880	1,252,520	1,370,160
March	638,457	698,066	729,843	825,465	887,558	1,011,743	1,073,835	1,198,020	1,322,205	1,446,390
April	568,537	621,618	649,915	735,065	790,357	900,942	956,235	1,066,820	1,177,405	1,287,990
May	588,202	643,119	672,394	760,490	817,695	932,105	989,310	1,103,720	1,218,130	1,332,540
June	615,733	673,220	703,866	796,085	855,967	975,732	1,035,615	1,155,380	1,275,145	1,394,910
July	670,795	733,423	766,809	867,275	932,513	1,062,988	1,128,225	1,258,700	1,389,175	1,519,650
August	560,700	599,148	659,223	720,900	760,950	841,050	881,100	961,200	1,041,300	1,121,400
September	489,300	522,852	575,277	629,100	664,050	733,950	768,900	838,800	908,700	978,600

TABLE D-9 Monthly Release Volumes (in ac-ft) by Water Year Release for Alternative E with Low Summer Flows

	Water Year Release (maf)									
Month	7	7.48	8.23	9	9.5	10.5	11	12	13	14
October	480,000	480,000	642,583	642,583	642,583	642,583	642,583	642,583	642,583	642,583
November	500,000	500,000	641,532	641,532	641,532	641,532	641,532	641,532	641,532	641,532
December	600,000	600,000	715,885	715,885	715,885	715,885	715,885	715,885	715,885	715,885
January	683,468	747,279	781,296	883,660	950,130	1,083,070	1,149,540	1,282,480	1,415,420	1,537,189
February	604,808	661,275	691,377	781,960	840,780	958,420	1,017,240	1,134,880	1,252,520	1,381,331
March	638,457	698,066	729,843	825,465	887,558	1,011,743	1,073,835	1,198,020	1,322,205	1,446,390
April	714,353	775,725	823,598	922,047	985,976	1,113,833	1,177,761	1,305,618	1,433,475	1,487,603
May	739,062	802,556	852,085	953,940	1,020,080	1,152,359	1,218,499	1,350,778	1,483,058	1,537,189
June	773,654	840,120	891,967	998,589	1,067,825	1,206,296	1,275,531	1,414,002	1,487,603	1,487,603
July	426,654	463,308	491,901	550,701	588,883	665,246	703,428	779,792	878,014	1,052,213
August	426,654	463,308	491,901	550,701	588,883	665,246	703,428	779,792	878,014	1,052,213
September	412,890	448,363	476,032	532,937	569,885	643,787	680,738	754,638	849,691	1,018,269

TABLE D-10 Monthly Release Volumes (in ac-ft) by Water Year Release for Alternative F

	Water Year Release (maf)									
Month	7	7.48	8.23	9	9.5	10.5	11	12	13	14
October	444,800	444,800	493,860	493,860	493,860	493,860	493,860	493,860	493,860	493,860
November	430,450	430,450	477,930	477,930	477,930	477,930	477,930	477,930	477,930	477,930
December	444,800	444,800	493,860	493,860	493,860	493,860	493,860	493,860	493,860	493,860
January	399,780	444,800	493,860	566,090	587,333	697,737	762,803	849,488	1,127,401	1,405,315
February	491,970	541,610	599,950	679,580	713,503	847,624	926,667	1,388,429	1,388,429	1,388,429
March	701,570	767,290	848,690	954,120	1,009,323	1,199,050	1,310,865	1,537,189	1,537,189	1,537,189
April	830,780	904,790	999,830	1,118,560	1,189,069	1,412,584	1,487,603	1,487,603	1,487,603	1,487,603
May	1,101,480	1,170,880	1,279,340	1,390,680	1,521,482	1,576,859	1,576,859	1,576,859	1,576,859	1,576,859
June	1,123,140	1,176,360	1,259,500	1,344,870	1,487,603	1,487,603	1,487,603	1,487,603	1,487,603	1,487,603
July	347,480	388,920	432,370	498,850	514,205	610,863	667,828	743,719	987,030	1,230,340
August	347,480	388,920	432,370	498,850	514,205	610,863	667,828	743,719	987,030	1,230,340
September	336,270	376,380	418,440	482,750	497,627	591,167	646,294	719,741	955,206	1,190,672

TABLE D-11 Monthly Release Volumes (in ac-ft) by Water Year Release for Alternative G

	Water Year Release (maf)									
Month	7	7.48	8.23	9	9.5	10.5	11	12	13	14
October	635,300	635,300	699,000	699,000	699,000	699,000	699,000	699,000	699,000	699,000
November	635,300	635,300	699,000	699,000	699,000	699,000	699,000	699,000	699,000	699,000
December	615,305	615,305	677,000	677,000	677,000	677,000	677,000	677,000	677,000	677,000
January	580,721	635,300	699,000	786,355	843,132	956,685	1,013,462	1,127,015	1,240,568	1,354,121
February	524,523	614,396	676,000	710,256	761,538	864,103	915,385	1,017,949	1,120,513	1,223,077
March	580,721	635,300	699,000	786,355	843,132	956,685	1,013,462	1,127,015	1,240,568	1,354,121
April	561,988	635,300	699,000	760,989	815,934	925,824	980,769	1,090,659	1,200,549	1,310,440
May	580,721	573,497	631,000	786,355	843,132	956,685	1,013,462	1,127,015	1,240,568	1,354,121
June	561,988	635,300	699,000	760,990	815,934	925,824	980,768	1,090,659	1,200,549	1,310,440
July	580,721	614,396	676,000	786,355	843,132	956,685	1,013,462	1,127,015	1,240,568	1,354,120
August	580,721	635,300	699,000	786,355	843,132	956,685	1,013,462	1,127,015	1,240,568	1,354,120
September	561,991	615,306	677,000	760,990	815,934	925,824	980,768	1,090,658	1,200,549	1,310,440

TABLE D-12 Minimum Release Constraints (cfs) Used for Each Alternative

Alternative	Minimum Release (cfs)
A	6,562.50
B	6,500.00
C	6,520.83
D[a]	6,520.83
E	6,520.83
F	5,000.00
G	8,000.00

[a] For Alternative D, with steady weekend flows for invertebrate production, the May–August minimum release constraint is 8,000 cfs.

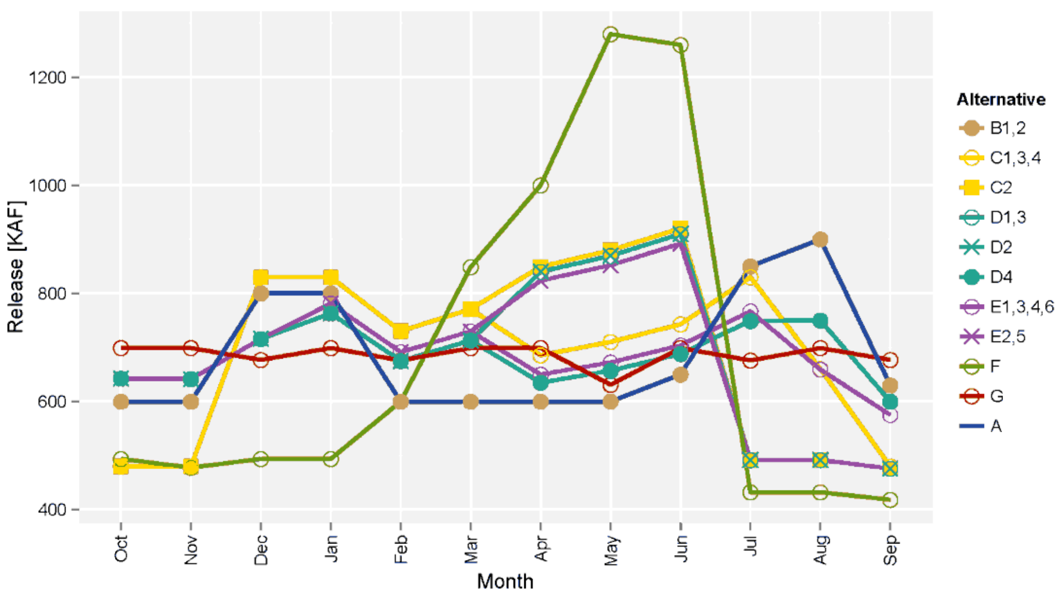

FIGURE D-2 Monthly Releases in kaf for Each Alternative in an 8.23-maf Release Year (Note that long-term strategies C2, D1, D2, D3, E2, and E5 are shown with the monthly distributions when low summer flows are implemented. Low summer flows would not be implemented in all years.)

D.1.4.1 Experimental Components Modeled in CRSS

Specific to the LTEMP DEIS, both experimental treatments—low summer flows and May through August steady weekend flows for invertebrate production—were incorporated into CRSS. The following sections discuss how these experimental components were modeled in CRSS.

Low Summer Flows

Low summer flows were implemented in CRSS as an experimental component under Alternatives C, D, and E. The objective of low summer flows is to produce warmer temperatures (i.e., greater than 13°C [55°F] for Alternatives C and E and greater than 14°C [57°F] for Alternative D) at the confluence with the Little Colorado River (T_{LCR}) in July, August, and September. In May, these alternatives would switch to a low summer flow pattern, releasing less water during these months, if all three of the following conditions are true: (1) the projected annual water year release is <10 maf, (2) projected T_{LCR} is cold[4] in any of the three target months using the base release pattern, and (3) switching to the low summer flow pattern would result in warm[5] temperatures in all three of the target months. Alternatives that have low summer flows as an experimental component would use the base release tables, unless these three conditions were met. For example, Alternative E (long-term strategy 2) would use release volumes from Table D-8, but would switch to the release volumes in Table D-9 if the above conditions were met. Note that Alternatives C and E were modeled with low summer flows during the entire 20-year LTEMP period, whereas Alternative D was modeled with implementation of low summer flows only during the second 10 years of the LTEMP period.

The projected temperature conditions were calculated using regression equations that considered monthly elevations and releases and the calendar year inflow at Lake Powell, and were empirically developed from observed conditions. The regression equations[6] to solve for T_{LCR} in July, August, and September were as follows:

July: $T_{LCR} = T_o + 3.791 / (0.000461 \times \textit{Apr Projected Release}_{JUL})^{0.63} \times (36.31 - T_o)$,
where: $T_o = 249.4 - (0.0668 \times \textit{Apr Projected EOM Elev}_{JUL}) + (3.766\text{E-}7 \times \textit{Apr Projected CY Inflow})$

4 Cold is defined as <13°C (55°F) for long-term strategies C2, E2, and E5 and <14°C (57°F) for long-term strategies D1, D2, and D3.

5 Warm is defined as >13°C (55°F) for long-term strategies C2, E2, and E5 and >14°C (57°F) for long-term strategies D1, D2, and D3.

6 Regression equations were log-transformed for inclusion into CRSS.

August: $T_{LCR} = T_o + 3.791 / (0.000461 \times \mathit{Apr\ Projected\ Release}_{AUG})^{0.63} \times (34.81 - T_o)$,
where: $T_o = 297.2 - (0.0802 \times \mathit{Apr\ Projected\ EOM\ Elev}_{AUG}\text{"}) + (4.915\text{E-}7 \times \mathit{Apr\ Projected\ CY\ Inflow})$

September: $T_{LCR} = T_o + 3.791 / (0.000476 \times \mathit{Apr\ Projected\ Release}_{SEP})^{0.63} \times (30.01 - T_o)$,
where: $T_o = 327.9 - (0.0886 \times \mathit{Apr\ Projected\ EOM\ Elev}_{SEP}) + (5.342\text{E-}7 \times \mathit{Apr\ Projected\ CY\ Inflow})$

where:

T_{LCR} = temperature at the Little Colorado River Confluence, °C

T_o = Lake Powell release temperature, °C

EOM Elev = Lake Powell projected end-of-month elevation, ft

CY Inflow = Lake Powell projected calendar year inflow, ac-ft

Release = Lake Powell projected monthly release volume, ac-ft

Steady Weekend Flows For Invertebrate Production

Steady weekend flows for invertebrate production were an experimental component of Alternative D. For the long-term strategy that included these flows, the May–August minimum release constraint was increased to 8,000 cfs.

D.1.5 Input Hydrology

The future hydrology used as input to the model consisted of samples taken from the historical record of natural flow in the river system over the 105-ear period from 1906 through 2010, from 29 individual inflow points (or nodes) on the system. The locations of the hydrologic input sites are shown in Figure D-3.

Typically, CRSS is run with the full suite of available natural flow traces created using a resampling technique known as the Indexed Sequential Method (ISM) (Ouarda et al. 1997). Using the ISM on a 105-year record (1906–2010) results in 105 inflow traces (i.e., plausible inflow sequences). For this DEIS, however, due to the complexity, resource and timing constraints, and number of loosely coupled models used to analyze other resource impacts, every fifth trace from the 105 natural flow traces was selected, resulting in 21 traces.

Figures D-4 and D-5 compare the differences between using 105 traces versus 21, and indicate that the distribution of 21 traces is very similar to the distribution of the full 105 traces for Lake Powell annual inflow, annual and monthly releases, and end of December pool elevation.

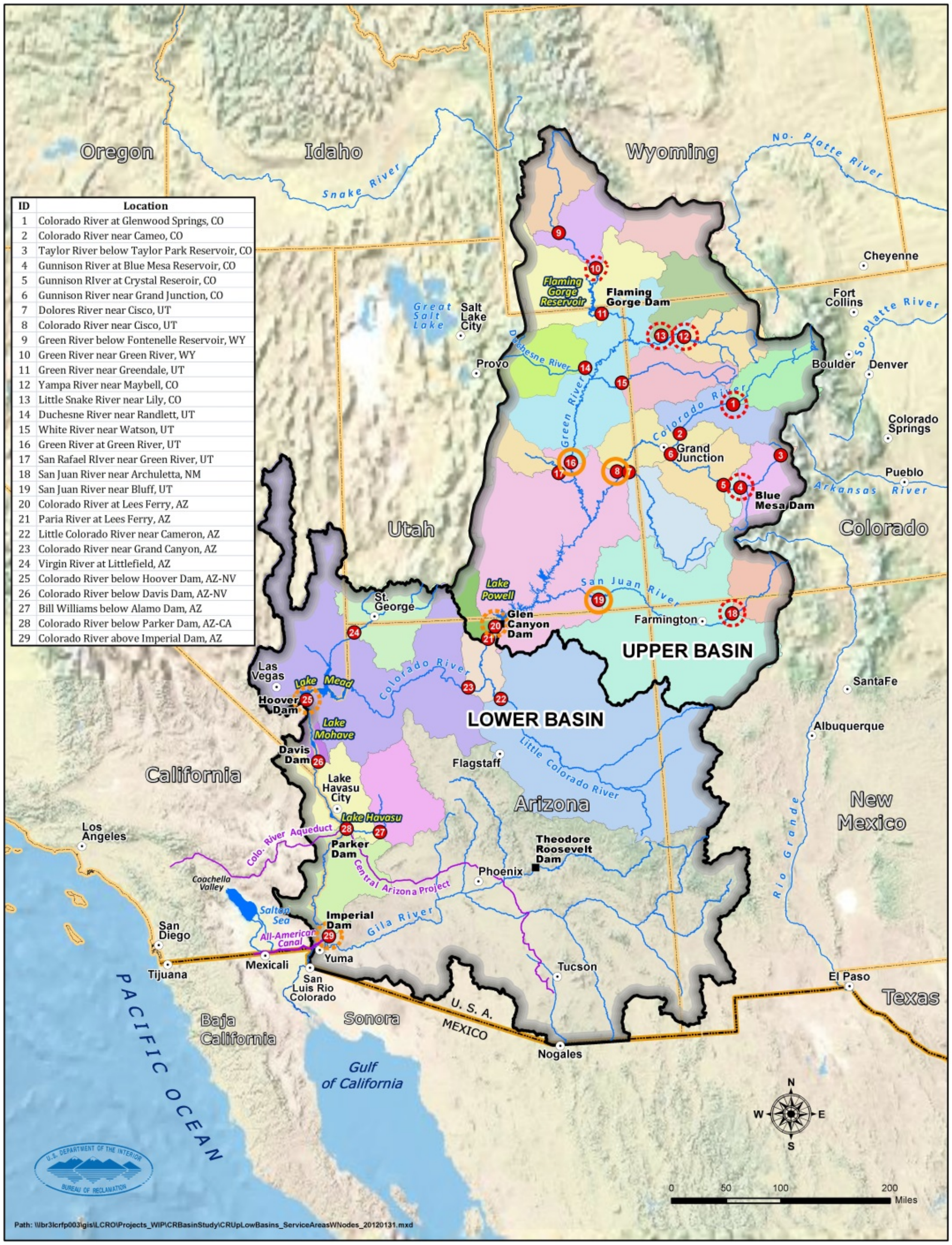

FIGURE D-3 Locations of CRSS 29 Natural Flow Nodes

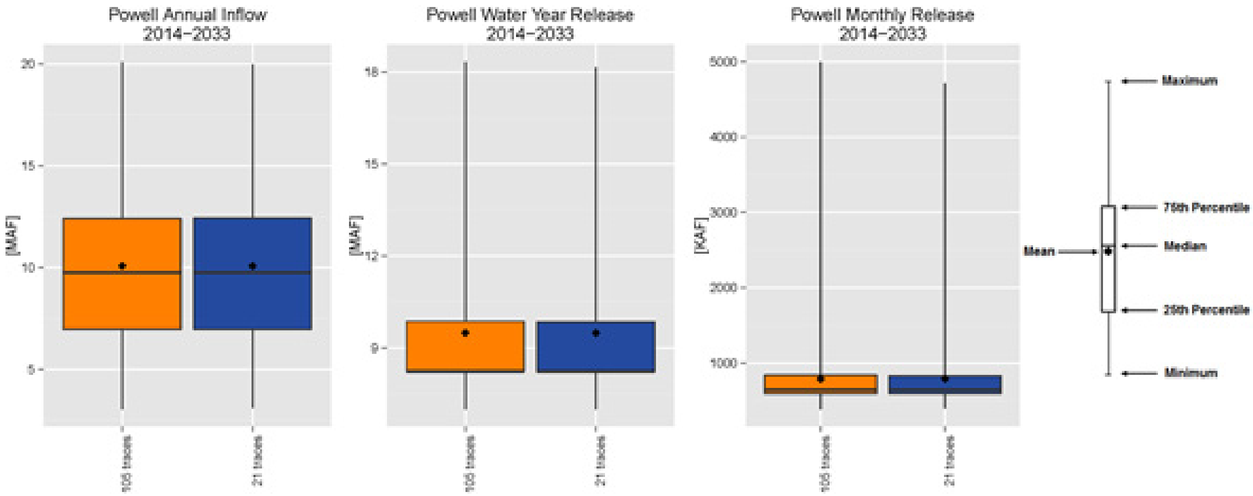

FIGURE D-4 Comparison of CRSS Results Generated Using 105 Traces (orange) and 21 Traces (blue) for Lake Powell Annual Inflow (left), Lake Powell Water Year Release Volume (center) and Lake Powell Monthly Release Volume (right)

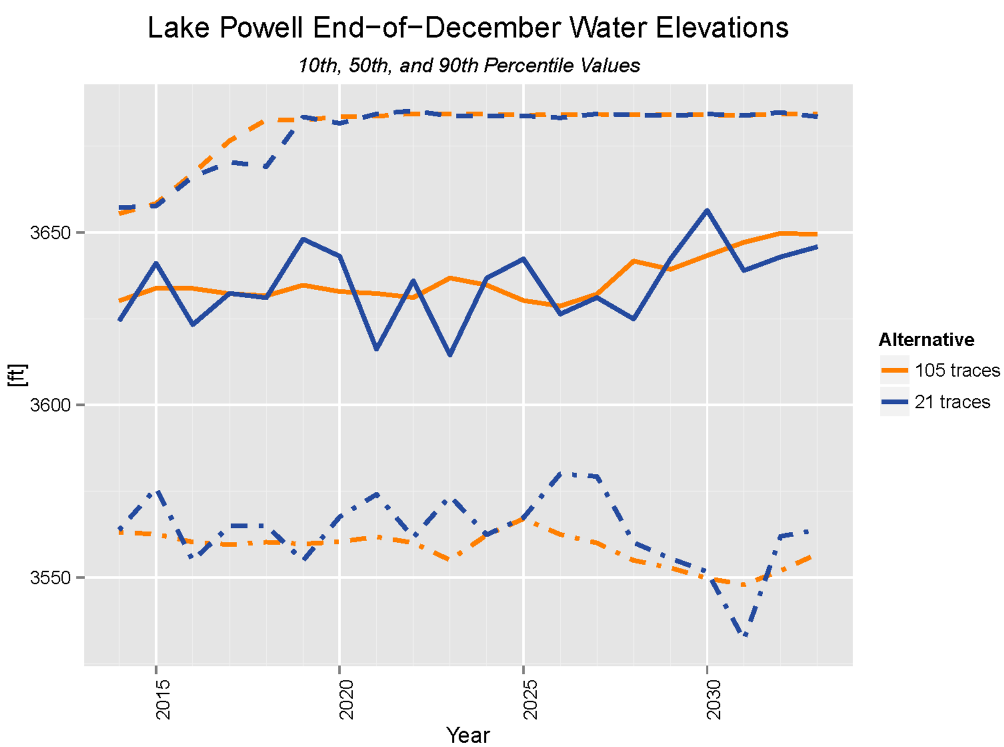

FIGURE D-5 Comparison of CRSS Results Generated Using 105 Traces (orange) and 21 Traces (blue) for Lake Powell End of December Water Elevations at the 10th (dashed and dotted lines), 50th (solid lines), and 90th (dashed lines) Percentiles

D.1.6 Input Demands

The LTEMP modeling utilized the Basin Study Current Projected demand scenario (Reclamation 2012b) for the input demands into CRSS. Table D-13 summarizes the demands by state.

D.1.7 Other Key Assumptions

A number of changes to CRSS were described in the Basin Study (Appendix G-2) including how the model treats implementation of Upper Colorado River water rights and intentionally created surplus.

Future water deliveries to Mexico were modeled as follows:

1. The model accounts for the entire delivery to Mexico at the Northerly International Boundary (NIB).

2. Water deliveries to Mexico are pursuant to the requirements of the 1944 Treaty. This provides annual deliveries of 1.5 maf to Mexico and up to 1.7 maf during Lake Mead flood control release conditions.

3. For modeling purposes, it is assumed that during shortage conditions, Mexico shares shortage in proportion to U.S. users in the Lower Basin (16.67 percent). This assumption is consistent with that used in the modeling supporting 2007 Interim Guidelines Final EIS (Reclamation 2007).[7]

4. Minute No. 318 and Minute No. 319 were not modeled as part of the LTEMP DEIS because modeling began before they could be incorporated into CRSS.

The Warren H. Brock Reservoir was assumed to operate every year beginning in 2013 and is assumed to conserve approximately 90 percent of non-storable flows. This reduces the average annual volume of non-storable flows delivered to Mexico from 73 kaf/yr (historical average from 1964 through 2010, excluding flood years on the Gila or flood control releases) to 7 kaf/yr.

Bypass of return flows from the Welton-Mohawk Irrigation and Drainage District to the Cienega de Santa Clara in Mexico was assumed to be 109 kaf/yr (historical average from 1990 through 2010) and was not counted as part of the 1944 Treaty delivery to Mexico.

The Yuma Desalting Plant was assumed to not operate during the LTEMP period.

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[7] Allocation of Colorado River water to Mexico is governed by the 1944 Treaty. Reclamation's modeling assumptions are not intended to constitute an interpretation or application of the 1944 Treaty or to represent current United States policy or a determination of future United States policy regarding deliveries to Mexico.

TABLE D-13 Input Demands, by State (in ac-ft)

	Upper Division States				Lower Division States		
Year	CO	NM	UT	WY	AZ[a]	CA	NV
2013	2,524,327	592,772	1,017,031	539,545	2,800,000	4,400,000	300,000
2014	2,524,552	601,496	1,018,144	539,755	2,800,000	4,400,000	300,000
2015	2,524,776	610,220	1,019,258	539,965	2,800,000	4,400,000	300,000
2016	2,536,669	618,944	1,020,371	542,900	2,800,000	4,400,000	300,000
2017	2,548,562	627,668	1,021,485	545,835	2,800,000	4,400,000	300,000
2018	2,560,455	636,392	1,022,599	548,769	2,800,000	4,400,000	300,000
2019	2,572,347	645,116	1,023,712	551,704	2,800,000	4,400,000	300,000
2020	2,584,240	653,840	1,029,826	554,639	2,800,000	4,400,000	300,000
2021	2,596,133	658,483	1,033,820	557,574	2,800,000	4,400,000	300,000
2022	2,608,026	663,126	1,037,813	560,509	2,800,000	4,400,000	300,000
2023	2,619,919	667,769	1,041,807	563,443	2,800,000	4,400,000	300,000
2024	2,631,812	672,412	1,045,801	566,378	2,800,000	4,400,000	300,000
2025	2,643,705	677,055	1,049,794	569,313	2,800,000	4,400,000	300,000
2026	2,655,597	681,698	1,053,788	572,248	2,800,000	4,400,000	300,000
2027	2,667,490	686,341	1,057,781	575,183	2,800,000	4,400,000	300,000
2028	2,679,383	690,984	1,061,775	578,117	2,800,000	4,400,000	300,000
2029	2,691,276	695,627	1,065,769	581,052	2,800,000	4,400,000	300,000
2030	2,703,169	700,270	1,074,762	583,987	2,800,000	4,400,000	300,000
2031	2,715,062	702,863	1,080,156	586,922	2,800,000	4,400,000	300,000
2032	2,726,954	705,456	1,085,550	589,857	2,800,000	4,400,000	300,000
2033	2,738,847	708,049	1,090,943	592,791	2,800,000	4,400,000	300,000

[a] There are an additional 50,000 ac-ft/yr of Arizona demands within the Upper Basin, represented in CRSS.

D.2 SUPPLEMENTAL INFORMATION ON IMPACT MODELING

The following sections provide more detailed information on the impacts of the different LTEMP alternatives, particularly for low summer flows, the carryover equalization release metric, and alternative-specific comparisons to Alternative A (no-action alternative). These results supplement those covered in Section 4.1 of this DEIS.

D.2.1 Low Summer Flows

During years with low summer flows, releases would be lower than typical in July, August, and September and proportionally higher in May and June, in order to maintain the same annual release volume. In years when the required annual release volume is not known until the end of the water year (e.g., during balancing or equalization), the low summer flows monthly volumes may end up being higher or lower than those originally projected in April, due to changing hydrologic conditions. Figure D-6 shows the modeled frequency of occurrence of low summer flows. Note that Alternatives C and E were modeled with implementation of low summer flows during the entire 20-year period, whereas Alternative D was modeled with low

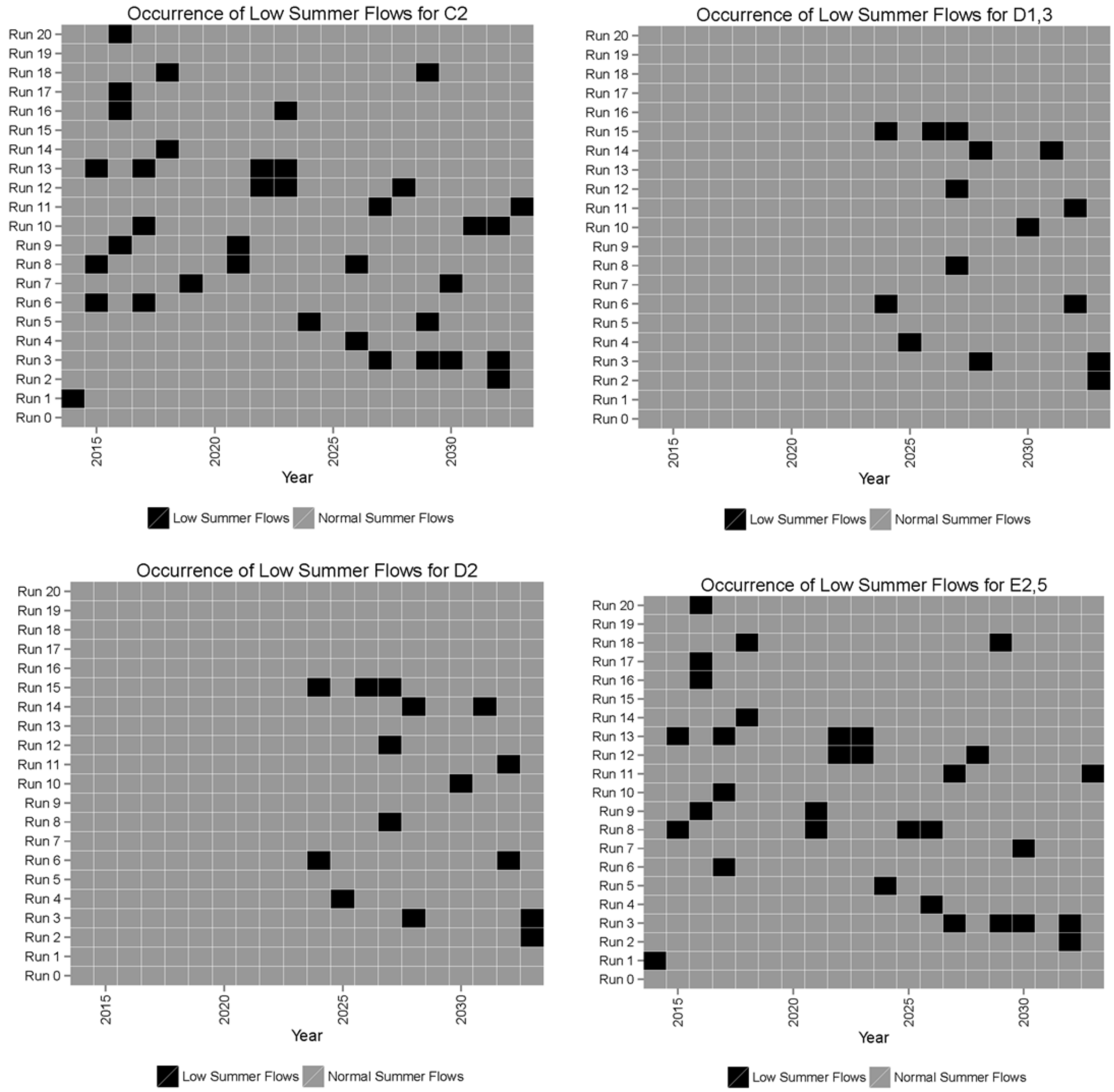

FIGURE D-6 Occurrences of Low Summer Flows in Applicable Alternatives (Numbers after alternative letter designations represent the long-term strategies that would implement low summer flows.)

summer flows only during the second 10 years of the LTEMP period. For those alternatives with low summer flows, the modeled number of low summer flows in the 20-year period ranged from zero to four occurrences per trace. Depending on the alternative, the average ranged from 0.7 to 1.8 low summer flows per 20-year run.

D.2.2 Modeled Annual Releases Extending Beyond the End of the Water Year

The frequency (Figure D-7) and volume (Figure D-8) of exceptions to meeting the annual release target volumes specified by the Interim Guidelines were one of the calculated water

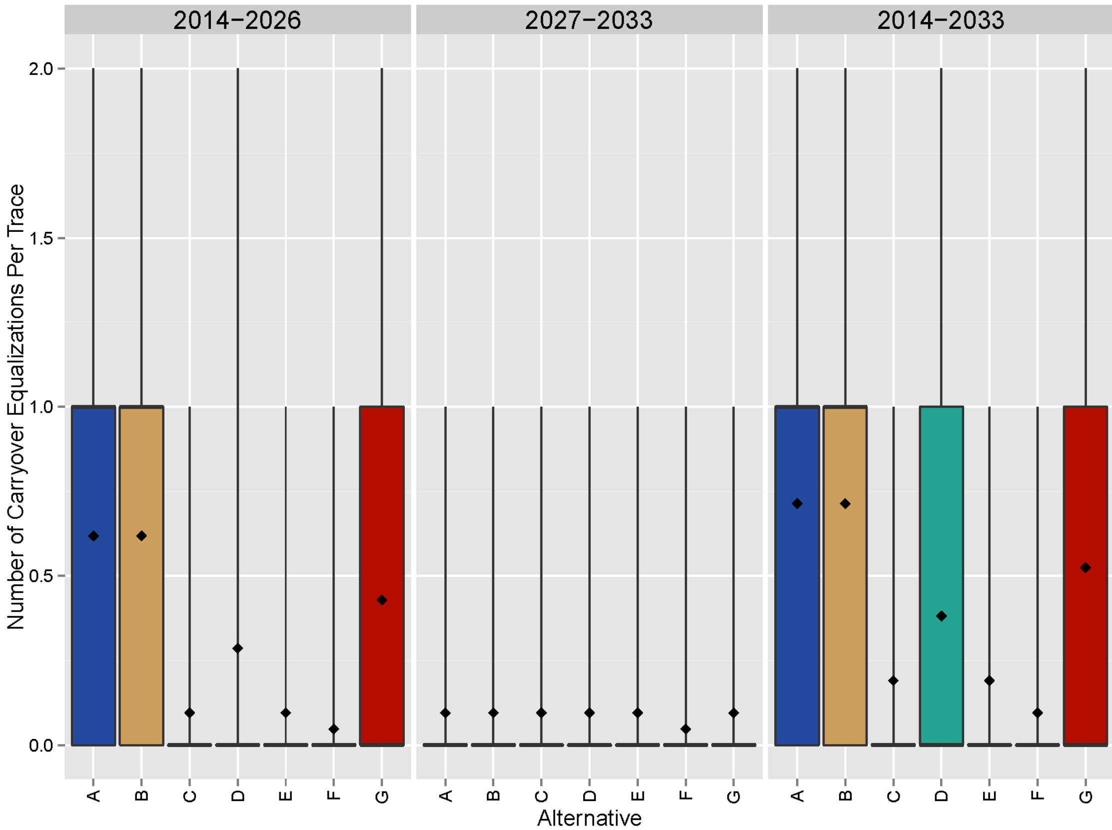

FIGURE D-7 Frequency of Occurrence of Modeled Annual Releases Extending beyond the End of the Water Year per 20-Year Trace for Each of the Alternatives (See Figure 4-2 for an explanation of how to interpret this graph. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum.)

resource metrics. Note that there is the possibility of exceptions occurring under all alternatives, including Alternative A (the no-action alternative).

D.2.3 Lake Elevation

The following figures present end-of-December elevations for Lake Powell (Figures D-9 through D-14) and percent of traces below Lake Powell's minimum power pool (Figures D-15 through D-20) for each alternative, and compares them to Alternative A. These graphs show different implementations of each alternative (referred to here as long-term strategies). These are given the letter designation of the alternative (A–G), and a number designating the long-term strategy for the alternative. See Section 4.1 and Appendix C for descriptions of the experiments included in each long-term strategy. For both of these parameters, only very small differences between Alternatives B-G and Alternative A were found.

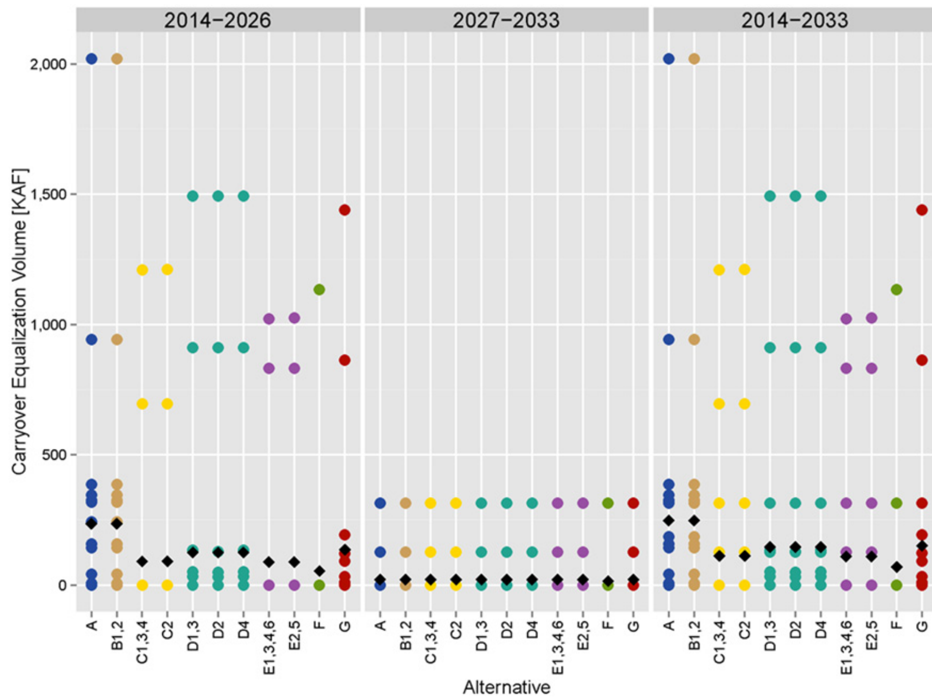

FIGURE D-8 Median Volume of Modeled Annual Releases Extending beyond the End of the Water Year Releases by Trace for Each of the Alternatives (Each value represents the median carryover equalization volume for one trace. Because there are few traces with more than one occurrence, the median value typically represents the only nonzero instance. For each alternative there are 21 possible carryover equalization values for each period and alternative combination [21 traces].)

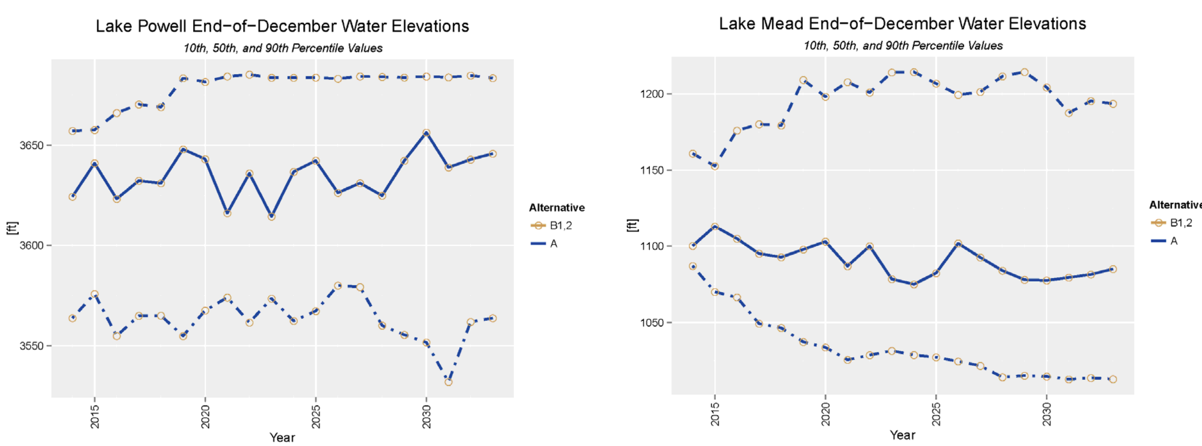

FIGURE D-9 Lake Powell (left) and Lake Mead (right) End-of-December Pool Elevation for 21 Hydrology Traces under Alternatives A and B

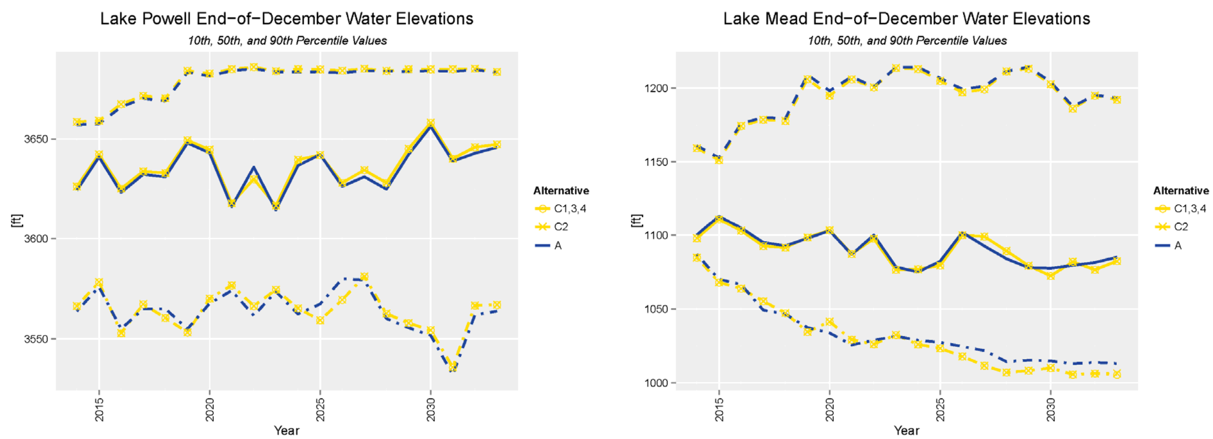

FIGURE D-10 Lake Powell (left) and Lake Mead (right) End-of-December Pool Elevation for 21 Hydrology Traces under Alternatives A and C

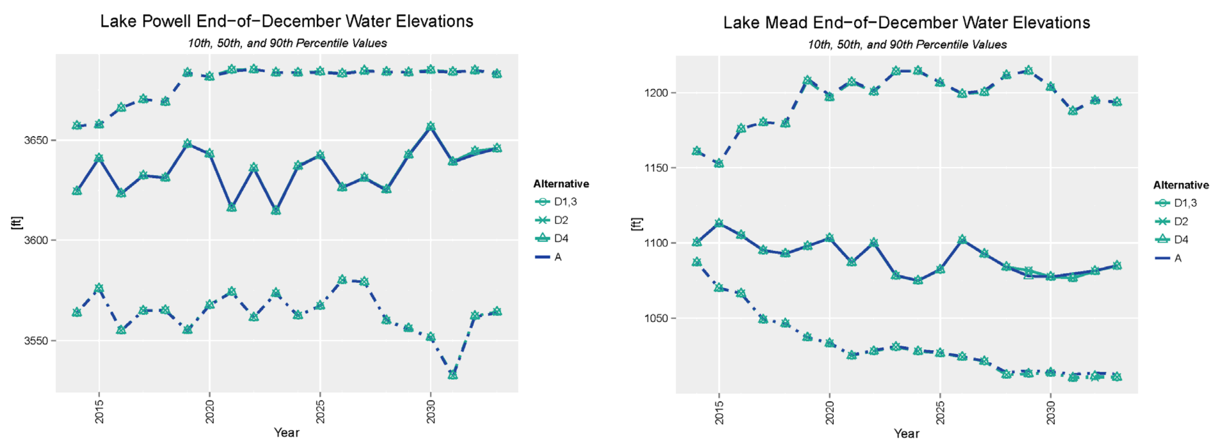

FIGURE D-11 Lake Powell (left) and Lake Mead (right) End-of-December Pool Elevation for 21 Hydrology Traces under Alternatives A and D

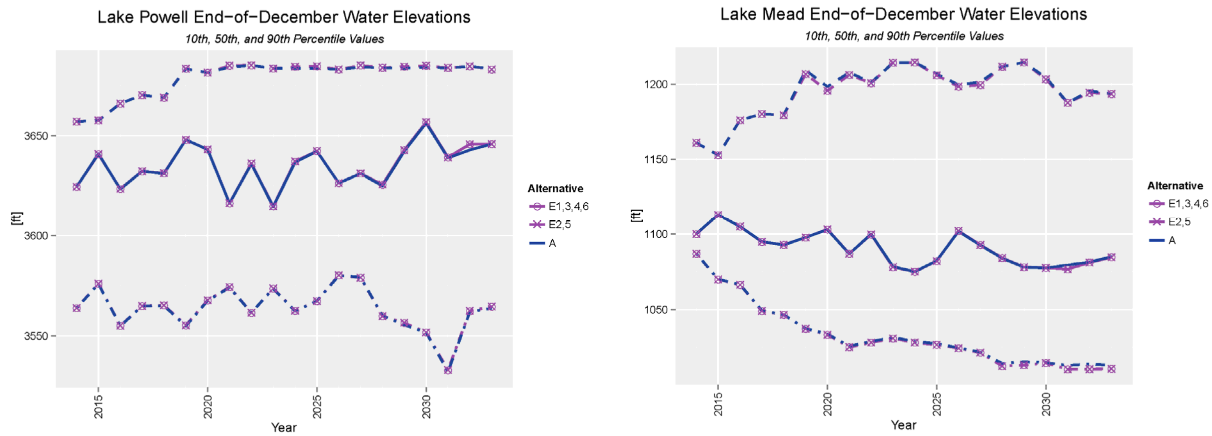

FIGURE D-12 Lake Powell (left) and Lake Mead (right) End-of-December Year Pool Elevation for 21 Hydrology Traces under Alternatives A and E

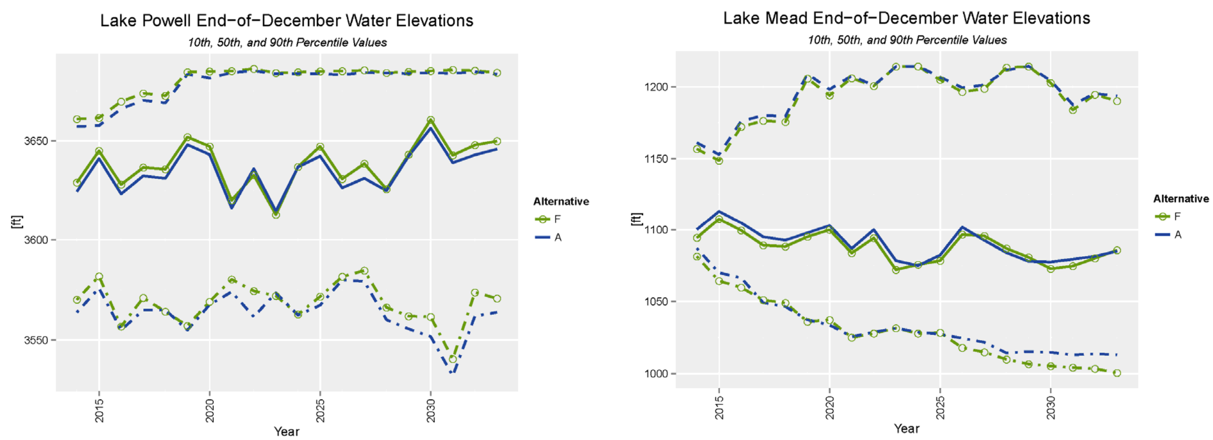

FIGURE D-13 Lake Powell (left) and Lake Mead (right) End-of-December Pool Elevation for 21 Hydrology Traces under Alternatives A and F

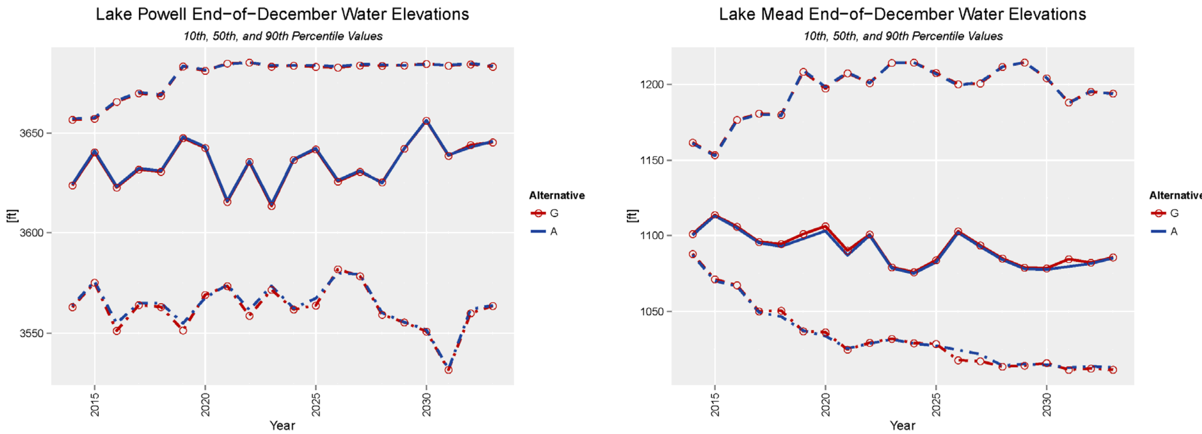

FIGURE D-14 Lake Powell (left) and Lake Mead (right) End-of-December Pool Elevation for 21 Hydrology Traces under Alternatives A and G

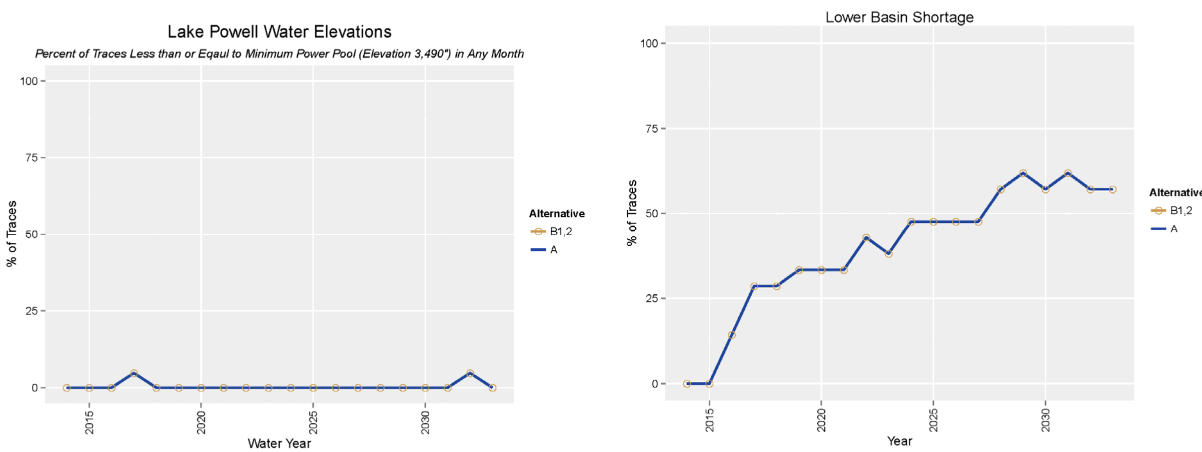

FIGURE D-15 Percent of Traces below Lake Powell's Minimum Power Pool (elevation 3,490 ft) (left) and Percent of Traces with a Lower Basin Shortage (any tier) (right) for 21 Hydrology Traces under Alternatives A and B

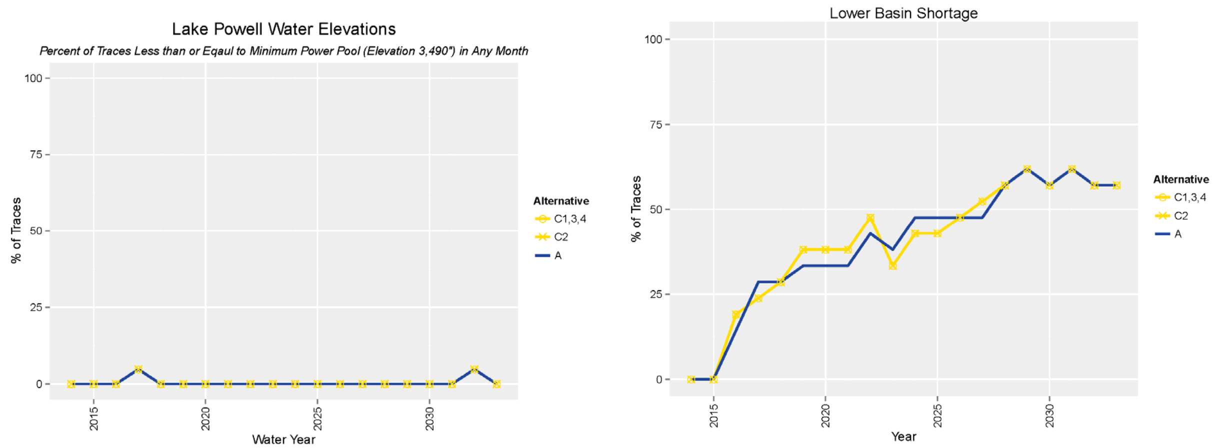

FIGURE D-16 Percent of Traces below Lake Powell's Minimum Power Pool (elevation 3,490 ft) (left) and Percent of Traces with a Lower Basin Shortage (any tier) (right) for 21 Hydrology Traces under Alternatives A and C

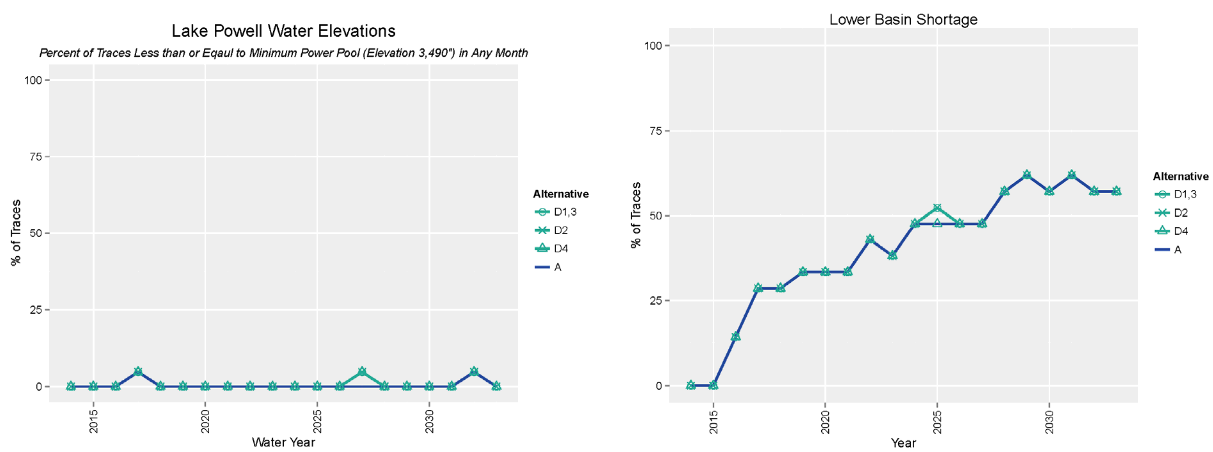

FIGURE D-17 Percent of Traces below Lake Powell's Minimum Power Pool (elevation 3,490 ft) (left) and Percent of Traces with a Lower Basin Shortage (any tier) (right) for 21 Hydrology Traces under Alternatives A and D

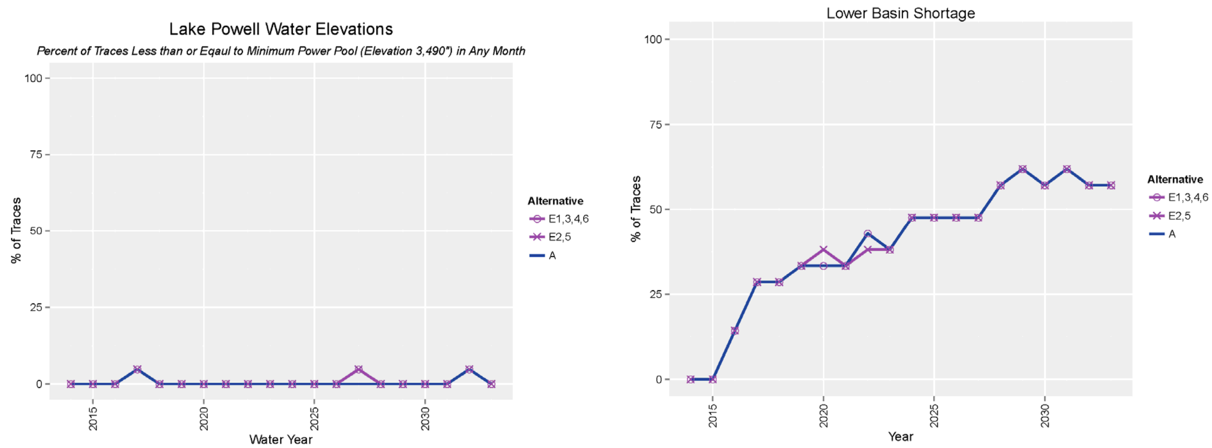

FIGURE D-18 Percent of Traces below Lake Powell's Minimum Power Pool (elevation 3,490 ft) (left) and Percent of Traces with a Lower Basin Shortage (any tier) (right) for 21 Hydrology Traces under Alternatives A and E

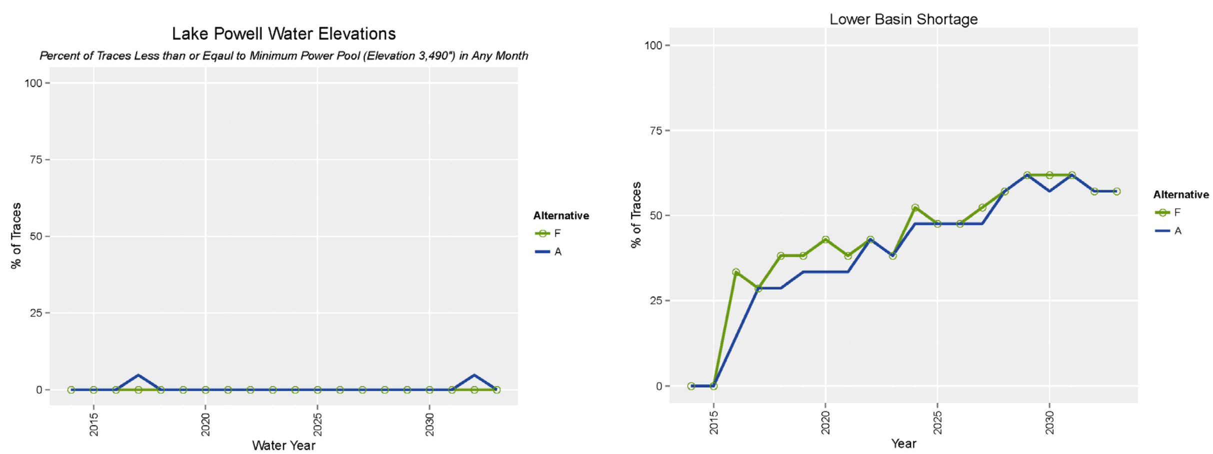

FIGURE D-19 Percent of Traces below Lake Powell's Minimum Power Pool (elevation 3,490 ft) (left) and Percent of Traces with a Lower Basin Shortage (any tier) (right) for 21 Hydrology Traces under Alternatives A and F

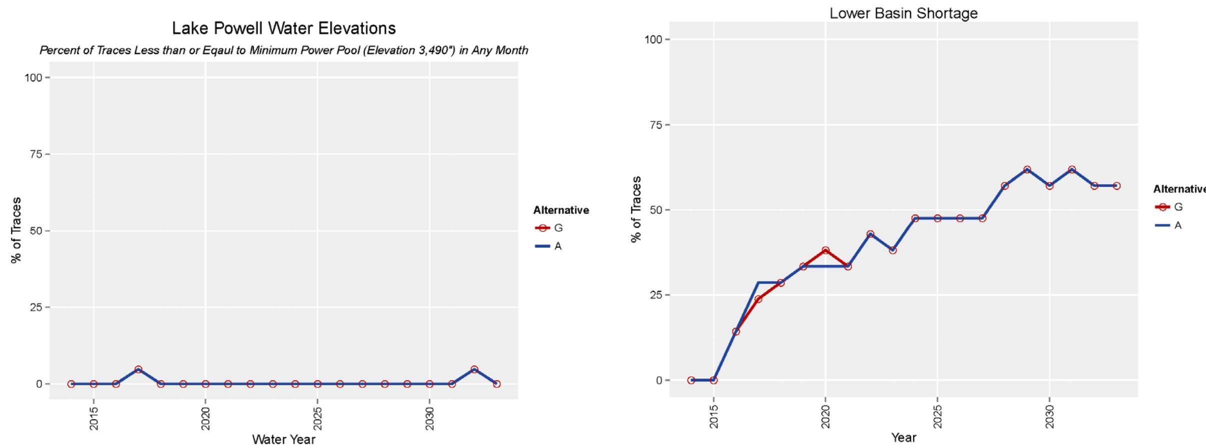

FIGURE D-20 Percent of Traces below Lake Powell's Minimum Power Pool (elevation 3,490 ft) (left) and Percent of Traces with a Lower Basin Shortage (any tier) (right) for 21 Hydrology Traces under Alternatives A and G

D.3 REFERENCES

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APPENDIX E:

SEDIMENT RESOURCES TECHNICAL INFORMATION AND ANALYSIS

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APPENDIX E:

SEDIMENT RESOURCES TECHNICAL INFORMATION AND ANALYSIS

E.1 INTRODUCTION

This technical appendix focuses on sediment resources. The sediment resource goal is to increase and retain fine sediment volume, area, and distribution in the Glen, Marble, and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes. One interpretation of this goal is to promote and maintain sandbars downstream of Glen Canyon Dam for the benefit of other resources. Currently, there is no peer-reviewed model or program that can simulate or predict sediment bar response to Glen Canyon Dam operations. Until such a model is available, other information and analyses were used in this draft environmental impact statement (DEIS) to analyze the effects alternatives would have on sediment resources. The sand budget model, which is peer reviewed and was used in the 2011 high-flow experiment (HFE) protocol environmental assessment (EA) (Reclamation 2011), provides the best available modeling method to estimate the effects of different flows on the potential for sandbar growth.

Seven alternatives were analyzed. Some of these alternatives would use condition-dependent or experimental elements that would be implemented under an adaptive management framework that would allow modification of flow and non-flow actions as new information is obtained. Critical uncertainties were identified that could lead to changes in flow and non-flow actions; these were used to identify multiple long-term strategies for those alternatives with condition-dependent actions (Alternatives B, C, D, and E). These long-term strategies were essentially different versions of the analyzed alternatives. The condition-dependent experimental elements included in the 19 strategies that were analyzed are presented in Appendix C; a full description of the alternatives can be found in Chapter 2 of this DEIS.

E.1.1 Analysis Period

Sediment analysis spanned water years 2014 through 2033 (i.e., October 1, 2013, to September 30, 2033) (Figure E-1). However, the hourly dam release data developed for the hydropower analysis (GTMax-Lite) followed a calendar year framework (i.e., January 1, 2013, through December 31, 2033). Development of sediment data for simulation input were analyzed in terms of sediment years (i.e., July 1, 2013, through June 30, 2033), which coincides with the accounting periods currently used by the Bureau of Reclamation (Reclamation) for determining whether or not a high-flow experiment (HFE) should be conducted (Russell and Huang 2010).

E.1.2 General Scope

In order to address uncertainty, the analysis conducted for this DEIS covered a range of hydrology scenarios and tributary sediment delivery scenarios. Hydrologic futures were developed using the Colorado River Simulation System (CRSS) (Appendix D). One-hundred and five 20-year hydrologic traces were developed from the 105-year period of record; for modeling (Section 4.1.1.1 of this DEIS), every fifth hydrologic trace was used, yielding 21 potential hydrologic futures to be analyzed.

Three sediment input time series were developed to address uncertainty in the future delivery of sand to the Colorado River from tributaries. Two main tributaries—the Paria River and the Little Colorado River—deliver sand to the Colorado River downstream of Glen Canyon Dam and upstream of Lake Mead. Three 20-year sediment traces were developed for the two tributaries (Section E.2.1.3), spanning the available historical data.

In summary, there were 19 long-term strategies, 21 hydrology traces per long-term strategy, and three sediment traces per hydrology trace. This produced 63 simulations per long-term strategy, 1,197 simulations in all.

E.2 METHODS

Resource models were used to evaluate and compare the impacts of alternatives. Figure E-2 illustrates the inputs, intermediate calculations, and output of the models. This appendix will describe and discuss those parts of the flowchart circled in red: the modified sand budget model (including development of model inputs) and the sediment metrics.

E.2.1 Sand Budget Model

E.2.1.1 Model Description

A reach-based sediment budget model for the Colorado River from Lees Ferry (river mile [RM] 0) to approximately Bright Angel Creek (RM 87) was developed by the U.S. Geological Survey (USGS) (Wright et al. 2010). Using gage data at RM 30, RM 61, and RM 87, the model was calibrated and validated to the time period of 2002–2009. The model uses empirically based rating curves, which are formulated on a particle-size-specific basis. On the basis of observed transport rates, the transport function changes when flows exceed 25,000 cfs. Initial sand bed size and thickness are user-specified for each reach (RM 0–RM 30, RM 30–RM 61, and RM 61–RM 87), and a budget is developed by tracking the incoming and outgoing suspended sand flux for each reach. The incoming sand flux for RM 0–RM 30 consists mainly of Paria River inputs, and ungaged tributaries in the reach are assumed to be 10% of Paria River inputs. The ungaged tributaries for RM 30–RM 61 are assumed to be negligible, so the flux into the reach equals the flux out of RM 0–RM 30. The flux into RM 61–RM 87 consists of the flux out of RM 30–RM 61, contributions from the Little Colorado River, and ungaged tributaries, which are assumed to be negligible. Figure E-3 provides a schematic of the sand budget model.

E.2.1.2 Sand Budget Model Modifications

The sand budget model has been updated to meet the specific analytical needs since its inception. During analysis for the 2011 High Flow Experiment (HFE) Environmental Assessment (EA) (Reclamation 2011), a protocol was developed to determine whether a HFE could be implemented to improve/maintain the sandbar sediment resource (Russell and Huang 2010). The model was updated to include the HFE protocol and to identify the largest HFE that could be implemented within each sediment accounting period without causing the Marble Canyon sediment balance to be negative for that period. Marble Canyon is the focus of the sediment balance because (1) the sand budget model was calibrated and validated for the first 87 mi downstream of Lees Ferry; and (2) the gage record for the Little Colorado River is relatively short, and therefore there is less confidence in using the data for predictive purposes. The protocol in the model assumes that the implementation of an HFE occurs on April 1 for the spring accounting period and on November 1 for the fall accounting period.

For the LTEMP DEIS, the water volumes used by each HFE were accommodated by adjusting monthly volumes in the rest of the water year instead of simply adjusting the releases for the remainder of the implementation month as was done for the HFE EA. One of two different reallocation schemes is implemented depending on the alternative: a sequential reallocation scheme or an average reallocation scheme.

The sequential reallocation scheme was applied to Alternatives A and B (because they have the same monthly release volume allocations). The months from which to reallocate water were specified in order, along with the minimum release volume for each month and the minimum release flow rate. Water was reallocated from the months, in order, until the water volume needed for an HFE was achieved. If the volume needed for an HFE could be borrowed from the first month in the list, then no water was borrowed from the following listed months. If the necessary HFE volume could not be taken from the first month without violating either the minimum monthly volume or the minimum release discharge, then the next month in the list was accessed for additional volume.

The average reallocation scheme was applied to the rest of the alternatives because their monthly release volume distributions differed from Alternative A. This method borrowed a percentage of the monthly volume from each month specified. The volume of water borrowed was not the same across months, but the percentage borrowed from each month was consistent; a higher monthly volume before reallocation means more water taken and applied to the HFE volume. There is a user-specified minimum release discharge that cannot be violated for the average reallocation scheme.

Another modification made to the sand budget model (which did not affect the triggering of an HFE) was to track the necessary parameters to determine whether a trout management flow (TMF) would be triggered for a water year. For a description of TMFs, see Chapter 2 of this DEIS. A simple binary file was developed to identify water years meeting the requirement for a TMF; parameters indicating trout recruitment and the triggering of a TMF are all flow related.

The primary results from the first iteration of the modified sand budget model are two files per simulation: one identifying the timing and size of HFEs, and one identifying timing of TMFs. This information is fed back to the GTMax-Lite model (Figure E-2) for refined hourly dam release hydrographs.

E.2.1.3 Modified Sand Budget Model Inputs

Primary model inputs to the sand budget model are (1) flow hydrographs and (2) tributary sand inputs. The initial conditions of sand bed thickness and average bed grain size were also specified; these values are constant across simulation and are not alternative dependent.

Flow Hydrographs

The model-predicted suspended sand transport rates were calibrated and validated (as part of the model development; Wright et al. 2010) at gage measurement locations, namely the gages at RM 30, RM 61, and RM 87. The flow hydrograph at these locations needs to be specified for the sand budget model and are developed using the Colorado River Flow, Stage, and Sediment (CRFSS) model. The CRFSS model has a one-dimensional unsteady-flow model component that routes a dam-release flow hydrograph and provides hydrographs at locations requested by the user. The CRFSS model uses average channel geometry based on previously measured cross-sections in Marble and Grand Canyons (Wiele and Smith 1996; Wiele et al. 2007). For each dam release hydrograph provided by GTMax-Lite (Figure E-2), there were three hydrographs developed by the CRFSS model (at RM 30, RM 61, RM 87) for use in the modified sand budget model.

Tributary Sand

Both the Paria River and the Little Colorado River have sediment records that were used to develop a time series of sand load (a sediment trace). Although the Little Colorado River record is for only 18.5 years, it is the best available data set. Three sediment traces were developed for each tributary to address uncertainty in future tributary sand delivery. Sediment data were obtained from two sources: published data from the Grand Canyon Monitoring and Research Center (GCMRC 2015) and from D. Topping (Topping 2014). The period of record for the two tributaries and the sources of the data are presented in Table E-1.

The model simulation period covers 21 calendar years, which corresponds to 41 sediment accounting periods, or ~20.5 sediment years (Figure E-2). An index sequential approach was used to develop statistics for each record. In general, an index sequential method cycles through each year in a historic record and generates time series (or traces) for a specific duration; for years toward the end of the record, the requisite time period is achieved by “wrapping around” to the beginning of the record. This technique is typically used for hydrologic data cycling through water years (Reclamation 2007; Ouarda et al. 1997), whereas the method is employed here for sediment data and cycles through sediment years. The “wrap around” for the sediment analysis means that for the Paria River, the fall 2013 accounting period is followed by the spring 1964 accounting period; likewise, for the Little Colorado River the fall 2013 accounting period is followed by the spring 1994 accounting period. The record for the Little Colorado River is short enough relative to the 21-year period that every index sequential sediment trace covers the entire period of record.

Paria River. Because fall 2013 is the first full accounting period for which an HFE would be considered in the simulation, only index sequential segments beginning with fall accounting periods are used in the statistical analysis. The three traces selected were approximately the 10%, 50%, and 90% non-exceedance traces from the index sequential statistics. The three selected traces for the Paria River also cover the entire period of record. Figure E-4 presents the sand input from the Paria River for the historical record grouped into accounting periods, along with the index sequential 41-accounting period (20.5-year) sand loads. Only the 20.5-year sand load sequences beginning with a fall accounting period are presented in Figure E-4; these are the data from which the statistics are developed for identifying three representative traces. Figure E-5 presents the cumulative sand load for the three traces that were identified for the use in the DEIS modeling. Again, these traces were identified based on cumulative sand load and to ensure the entire historical record is represented in the modeling.

These three traces are not consistently low, medium, and high relative to each other throughout the 20-year period. Moving from beginning to end of the simulation period, s1 (sediment trace 1) is not always less than s2, and s2 is not always less than s3. In fact, s3 is comparable to s2, except in the last couple of years when the s3 trace jumps significantly; this jump corresponds to the fall 1980 accounting period. In addition, s1 has the most sediment contributions for approximately the first 3 years. These are three different sediment traces that were selected to be representative of the historical record.

Once the three sets of 41 accounting periods were identified for use in the simulation, the necessary simulation records (traces) were completed by applying the appropriate sections of the historical record. The periods of record used for s1, s2, and s3 are presented in Table E-2.

Little Colorado River. The record for the Little Colorado River is shorter than the simulation period, so every trace covers the entire period of record. In addition, the HFE protocol as implemented in the modified sand budget model assesses the balance of sand in Marble Canyon to determine whether an HFE is simulated. The balance of sand in Eastern Grand Canyon—and therefore the sediment input from the Little Colorado River—is less critical to the simulations and analysis performed for this DEIS.

The index sequential method for the Little Colorado River was performed on a calendar year basis, and the simulation periods for s1, s2, and s3 are presented in Table E-3. Figure E-6 presents the sediment traces used as input for the modified sand budget model.

Initial Conditions

The initial conditions to be specified in the sand budget model for each reach are bed thickness and median bed sediment grain size, D_{50}. The initial conditions specified for the DEIS analysis come from the best available data nearest the simulation start date of January 1, 2013. Wright et al. (2010) found that varying initial bed D_{50} by ±10% from the initial estimated values (0.4, 0.3, and 0.3 mm for UMC, LMC, and EGC, respectively) yielded between 3 and 7% difference in total flux for the three reaches; varying initial bed thickness from the initial estimated values (0.4, 0.5, and 0.5 m for UMC, LMC, and EGC, respectively) by ±10% yielded a difference in total sand flux of less than 0.5%. The simulations conducted for this analysis used initial condition values for UMC, LMC, and EGC of 0.46, 0.38, and 0.43 mm, respectively, for grain size and 0.30, 0.37, and 0.27 m, respectively, for bed thickness.

High Flow Events

The modified sand budget model identified the largest HFE that would not violate water and sediment availability rules. The HFEs that the model considered are user specified. Eighteen HFEs that are specified for this analysis (Table E-4), and HFEs 1–13 are consistent with the HFEs considered for the HFE EA (Reclamation 2011). Longer-duration HFEs (A–E in Table E-4) were suggested for consideration in the DEIS, and two alternatives consider HFEs lasting longer than 96 hours: Alternative D and Alternative G. HFE C in Table E-4 was originally defined as lasting 240 hours at 45,000 cfs for Alternative G. Alternative D was crafted after seeing the results of the Alternatives A, B, C, E, F, and G (Section 2.2.4 of this DEIS), and HFE C in Table E-4 was defined as 250 hours for this alternative.

Proactive spring HFEs would be triggered based on hydrology. Conceptually, a large snowpack in the mountains leads to a prediction of a wet year, and if the predicted annual runoff volume is great enough (greater than 10 million ac-ft, or 10 maf) then a proactive spring HFE would be implemented. The purpose of this HFE is to redistribute the available bed sediment onto sandbars and channel margins so that it would be stored at elevations above those of the subsequent large runoff volume. The proactive spring HFE implemented in the model is identical to HFE 6 in Table E-4 in terms of peak discharge and duration at peak discharge.

E.2.2 Sediment Metrics

Prior to modeling for the LTEMP DEIS, a number of metrics were crafted to evaluate the alternatives in terms of their performance with regard to the sediment resource goal. The metrics developed prior to modeling were surrogates intended to be representative of sediment resource response; it was assumed that if the surrogate performed well, the sediment resource also would respond well. The metrics developed were the sand load index (SLI), the standard deviation of high flows (SDHF), and the sand mass balance index (SMBI).

E.2.2.1 Sand Load Index (SLI)

The potential for building sandbars was estimated using the SLI, which is a comparison of the mass of sand transported at RM 30 when river flows ≥31,500 cfs relative to the total mass of sand transported at all flows, as shown in equation 1:

$$SLI = \frac{\boldsymbol{Q_{s,Q>31.5}}}{\boldsymbol{Q_{s,total}}} \tag{1}$$

where:

SLI = sand load index

$Q_{s,Q>31.5}$ = sand flux at RM 30 when river flows at RM 30 are greater than 31,500 cfs

$Q_{s,total}$ = total sand flux at RM 30 during analysis period.

The index varies from 0 (no sand transported at flows ≥31,500 cfs) to 1 (all sand transported at flows ≥31,500 cfs). An SLI of 0 would indicate that there are no flows above 31,500 cfs during a simulation; the alternative that there are flows above 31,500 cfs but no sediment flux occurring is for all practical purposes impossible.

The larger the SLI for an alternative, the more potential there is for bar growth. The SLI only estimates the potential for (and not actual) bar growth, because all sandbars have a maximum potential deposition volume; the closer any given bar is to full, the less deposition will occur (Wiele and Torizzo 2005).

E.2.2.2 Standard Deviation of High Flows (SDHF)

This index was intended to represent a greater likelihood of more robust sandbars. Historical sandbar surveys indicate that individual bars respond differently to different HFEs (Hazel et al. 2010). Some sandbars are smaller after a 45,000 cfs event. Equation 2 shows how this value is calculated for each water year, and the metric is averaged across the 20-water-year analysis period.

$$SDHF = \sqrt{\frac{\mathbf{1}}{\mathbf{N-1}}\sum_{\mathbf{i=1}}^{\mathbf{N}}(\mathbf{x_i} - \mathbf{\bar{x}})^{\mathbf{2}}} \tag{2}$$

where:

SDHF = standard deviation of high flows

N = sample size (in this case, 63 per alternative)

x_i= individual observed peak discharge, cfs

$\bar{x}$ = sample mean of peak discharges, cfs.

E.2.2.3 Sand Mass Balance Index (SMBI)

This index quantifies the amount of sand that is left in storage in Marble Canyon (RM 0 to RM 61) at the end of a simulation relative to the amount of sand that is present at the beginning of the simulation. This is the most direct application of the modified sand budget model; it tracks the amount of sand that comes into the individual reaches compared to the amount of sand that leaves the individual reaches (Figure E-7). This index is not directly representative of the resource goal. However, this metric does provide insight into how the amount of sediment in Marble Canyon is affected by dam operations. If more sand comes into Marble Canyon than leaves Marble Canyon, there will be an increase in stored sand, and a positive SMBI. Conversely, a greater amount of sand leaving Marble Canyon than entering will yield a negative SMBI.

E.3 RESULTS

Two iterations of the modified sand budget model were completed for each simulation (Figure E-2). The first iteration determined the timing and size of triggered HFEs, as well as identifying whether TMFs would be triggered. This information was passed back to GTMax-Lite where the hourly dam release hydrographs were refined based on the HFE schedule and TMF schedule.

The second iteration of the modified sand budget model did not allow additional HFEs to be implemented because the refined GTMax-Lite dam releases already include the HFEs and TMFs. The second iteration was used to obtain sediment-related data for sediment metrics to be calculated for each alternative.

E.3.1 HFEs Determined by Alternative

The sediment metrics for each alternative are closely related to the number of HFEs that occur for the alternative. The number of HFEs is not a sediment metric itself, but understanding the HFEs that occur under an alternative helps to clarify the sediment metrics discussed in the following sections. The average number of HFEs that occur (across 63 simulations per alternative) is compared, along with the number of HFEs that occur based on sediment trace (average across 21 simulations). Results for long-term strategies C3, E3, E5, and E6 are not presented in this section, because HFEs are not included in these long-term strategies.

Figure E-8 presents the breakdown of the average number of HFEs for each long-term strategy (across 21 hydrology and 3 sediment traces) by HFE type (Table E-4). Only Alternatives D and G allow for HFEs longer than 96 hours, and Alternative G has the most HFEs on average. Alternatives A and B have the fewest HFEs on average. Under Alternative A (no-action alternative) the HFE protocol would expire in 2020, so a little more than half of the simulation period does not have HFEs simulated. Alternative B stipulates that HFEs would not be implemented more often than once every 2 years. This limits the number of HFEs to one-fourth of the simulation period. Alternative F has a 24-hour 45,000-cfs flow at the beginning of the spring peak period (e.g., on May 1) as part of the alternative definition. Those events are not captured in Figure E-8; this figure represents the sediment-triggered and hydrology-triggered HFEs identified from the modified sand budget model. More information on the alternative definitions can be found in Chapter 2 of this DEIS.

Figure E-9 compares the average number of HFEs simulated (not by HFE type) for the three different sediment traces. Remember that s1, s2, and s3 do not equate to low, medium, and high; they are three sediment traces intended to be representative of the historical sediment records in terms of exceedance probability, as well as ensuring that the entire period of record is represented by the three traces. Figure E-9 shows some variability among the sediment traces, although the general trends between alternatives as shown in Figure E-8 are maintained. Sediment trace s2 commonly has the lowest number of simulated HFEs. Sediment trace s1 has the most simulated HFEs for Alternatives A, B, and F. Sediment trace s3 has the most simulated HFEs for Alternatives C (except long-term strategy C4), D, and G. Sediment traces s1 and s3 are very similar for Alternatives E (except long-term strategy E4) and F with regard to the number of HFEs triggered.

The majority of HFEs are triggered in the fall, because sediment from the Paria is related to monsoonal precipitation and the majority of the sediment delivery occurs in the fall. Fall HFEs account for 77% of all HFEs simulated; the remaining 23% of HFEs that occur in the spring include proactive spring HFEs, which are triggered by hydrology (wet years) and not by sediment delivery.

E.3.2 Metrics

Plots have been developed for each metric to statistically describe the alternative performance from the 63 different simulations for each long-term strategy. The statistics represented in these plots include a weighting scheme based on each sediment trace's exceedance probability. The weighting scheme for the box and whisker plots is as follows: s1 = 0.1754, s2 = 0.6313, s3 = 0.1933. In addition, a different set of weights was used for a climate change analysis to represent the fact that future hydrology in the Upper Colorado River Basin is expected to be drier than the historical hydrology (Section 4.16.1.2 of this DEIS). Plots using climate change weighting are provided for each sediment resource metric in Section E.3.3.

The box and whisker plots provide information on the following statistical representations of the distribution of performance across 63 simulations per long-term strategy: minimum, maximum, mean, median, 25th percentile, and 75th percentile, as described in Figure E-10.

E.3.2.1 Sand Load Index (SLI)

The SLI as described in Section E.0 reflects the potential for sandbar growth. Figure E-11 presents SLI values for all long-term strategies. Overall, Alternative G has the highest SLI values, followed by Alternatives F, D, C and E. Alternatives A and B have the lowest SLI values, which is consistent with the number of HFEs that can be triggered under each alternative.

Figure E-11 matches the general pattern of the number of HFEs shown in Figure E-8. One notable exception is Alternative F; Figure E-8 represents the sediment-triggered and hydrology-triggered HFEs, whereas Figure E-11 includes data from the alternative-defined spring events that occur each year under Alternative F regardless of sediment availability.

There is a nonzero SLI for long-term strategies C3, E3, E5, and E6, even though there are no HFEs simulated for these long-term strategies. Some hydrologic years are wet enough to necessitate flows above 31,500 cfs being released from Glen Canyon Dam as normal (non-HFE) operations. The sand transported while flows are above 31,500 cfs under these conditions contributes to a nonzero SLI.

E.3.2.2 Standard Deviation of High Flows (SDHF)

As described in Section E.2.2.2, this metric was intended to reflect variability in flow, which was thought to be positively related to the ability to build more robust sandbars. Figure E-12 presents the statistical distribution of SDHF values for the long-term strategies, which is similar to the general pattern shown for the SLI in Figure E-11.

The SDHF mean is plotted against the SLI mean in Figure E-13. A strong correlation exists between the SDHF and the SLI. Therefore, the SDHF was not considered with the SLI for alternative comparison in this DEIS.

E.3.3 Sand Mass Balance Index (SMBI)

This metric does not represent the sediment metric directly (Section E.2.2.3); however, it does provide an index to relative changes in sediment balance that would result under different alternatives. If an alternative reduces the overall sediment balance (the amount of sediment in the sandbars and eddies, and on the channel bed) then this net depletion will result in less sediment being available for bar building during future HFEs.

The only long-term strategies that do not significantly reduce the sediment balance over the duration of the simulation period are those that do not have HFEs (long-term strategies C3, E3, E5, and E6), as shown in Figure E-14. The mass balance of sediment is affected by high flows. HFEs have been called a “double-edged sword” by Rubin et al. (2002) because they necessarily export relatively large volumes of sand in order to transfer sand to high-elevation portions of sandbars (Wright et al. 2008). There is an inverse relationship between sandbar building potential and sediment balance; more sandbar building potential reduces the sediment remaining within the channel. Figure E-15 plots the mean SMBI relative to the mean SLI. Although there is variation among the alternatives, a higher SLI tends to create a larger net deficit of sand (lower SMBI value) in Marble Canyon. Two exceptions are Alternatives B and D. Alternative B would produce a large net deficit in SMBI but has a relatively low SLI; the relatively low SLI is a result of the limited number of HFEs under this alternative, but this does not produce a correspondingly low SMBI because the larger daily fluctuations during intervening flows transport more sediment. Alternative D has relatively high SMBI and SLI values; more HFEs (including longer duration HFEs) yields the higher SLI value and the combination of relatively even monthly distributions along with relatively small daily fluctuations contributes to a higher SMBI.

E.3.4 Alternative Performance under Climate Change Scenarios

Weights were applied to hydrology traces to reflect expected changes in hydrology under climate change. This weighting scheme was intended to represent future hydrology in the basin, which is expected to be drier than the historical hydrology (Section 4.16.1.2 of this DEIS). Figure E-16 presents SLI values calculated under the long-term strategies using the climate change weights. Figure E-17 shows that there is little difference in long-term strategy performance in terms of SLI when comparing the climate change weights to the historical weights. The small difference that does exist could be described as a slight improvement in performance under the climate change weighting.

Figure E-18 presents SDHF values under long-term strategies when the climate change weights were used. Figure E-19 shows that there was little difference between SDHF values calculated using the climate change weights and those calculated using the historical weights. The most notable difference is a slight reduction in the 75th percentile, which indicates less variability in the metric when climate change weights are used.

Figure E-20 presents SMBI values under long-term strategies when the climate change weights were used. Figure E-21 shows that there was some difference between SMBI values calculated using the climate change weights and those calculated using the historical weights. When climate change weights were used, the interquartile ranges and the means were higher, which indicates less net depletion. Interestingly, the minima and maxima do not change appreciably, meaning these extremes are likely due to specific simulations (combination of hydrology and sediment traces).

E.3.5 Relative Impacts of Dam Operations and Hydrology on Performance

Modeling results were evaluated to determine the effect of the following management actions on sediment resources: proactive spring HFEs, spring HFEs, fall HFEs, TMFs, daily fluctuations and intervening flows, load-following curtailment, low summer flows, and general hydrology (wet vs. dry). These evaluations were made using the model runs of the various long-term strategies, which included some, but not necessarily all, elements. Additional modeling did not take place to answer these questions.

HFEs, whether they are proactive spring HFEs, spring HFEs, or fall HFEs, are the most influential management action in terms of sediment resources. Whether a given HFE type (magnitude and duration) occurs in the fall or the spring does not affect the sediment resource differently. The timing of sediment delivery from the Paria River (during the summer-fall monsoon season) leads to larger and more frequent fall HFEs, but that is due to input, not management actions.

TMFs did not show a significant impact on the sediment resource. This is due in part to the fact that one of the primary factors in triggering a TMF is a spring HFE, which, in the model, increased trout recruitment (Section 4.4.1.2 of this DEIS). Spring HFEs have a relatively large effect on the SLI and SMBI that tends to mask a TMF's impacts on sediment. Another reason TMFs have little impact on sediment because of their effect on release volume. In order to provide the flow for TMFs, the average flow in the remainder of the late spring/early summer period tends to be lower than if there were no TMF. The effect of higher flows for the TMFs and the lower flows means a very minor difference in net sediment transport.

Figure E-22 shows the time series of flow (Q) at RM 30, the SLI, and the SMBI for the simulation hydrology trace 1/sediment trace 3 (t01s3) for the period March 1, 2021, to August 1, 2021. Long-term strategies C1 and C2 are plotted for comparison; both simulations have the same HFE triggered in spring 2021, but TMFs are implemented under C1 but not C2. In the figure, the TMF flows can be seen in early May, June, and July in the top graph. Notice the time series of SLI and SMBI show a strong signal response in early April due to the HFE, and practically no signal response from the TMF flows.

Alternatives C and E differ in daily fluctuation levels, as well as monthly volume allocations; this is the best comparison we can make (without performing targeted modeling) on the effects of daily fluctuations. Alternative C has lower daily fluctuations than Alternative E, but has relatively high spring volume compared to the more even monthly pattern of Alternative E. Although lower daily fluctuations reduce sediment transport, higher monthly volumes increase transport. It was not possible to reconcile the relative importance of daily fluctuations and monthly volume allocations without additional modeling. However, a comparison of Alternative C and Alternative E using the long-term strategy where no HFEs are allowed (long-term strategies C3 and E3) was made. This comparison takes into account both daily fluctuations and monthly volume allocations. There was no difference in SMBI values between long-term strategies C3 and E3 (Figure E-23), and there was a minor difference in SLI values (Figure E-24). Because there are no HFEs in long-term strategies C3 and E3, all of the values for SLI are below 0.2 and any differences between these alternatives are minor.

Load-following curtailment is a management action intended to retain sediment for HFEs by reducing daily fluctuations before and/or after the HFE for a period of weeks or months. Load-following curtailment is specified as fluctuations being limited to ±1,000 cfs about the mean daily flow (a 2,000 cfs range of fluctuation). This management action does not appear to make a difference in the modeled metric values, because an HFE will necessarily reduce the non-HFE mean flow around which daily fluctuations occur; the daily fluctuations associated with lower means tend to have fluctuation ranges not much greater than the ±1,000 cfs specified for load-following curtailment. Figure E-25 shows the smaller fluctuation range leading up to a fall

HFE and the associated impact on SLI and SMBI (hydrology trace 6, sediment trace 3). Long-term strategies E1 and E2 are compared here, but the same comparison could be made using other long-term strategies (C1 and C2 or D1 and D2) with similar trends. Although there are differences in metric values between E1 and E2 for the months following the HFE, the SMBI is different by only 9 ktons at the end of the water year, and the SLI is the same by the end of the water year.

Low summer flows are a management action intended to provide warmer water for humpback chub during the summer. These lower flows would also be expected to conserve sediment inputs during the monsoon period. Implementing low summer flows in the summer requires increasing average monthly release volumes in other non-summer months (especially in the spring), thereby counteracting, in the long term, any short-term increase in sediment conservation (Figure E-26).

Annual inflow volume that reflects annual variation in precipitation and runoff is the main driving force on sediment processes. Release volumes are governed by legal release requirements (Section 1.9 of this DEIS). For the SLI, wetter hydrology means a lower metric value (Figure E-27). This is true for the long-term strategies that do not have limitations on the number of HFEs that can be triggered. The trend lines with a positive slope in Figure E-22 are Alternative A (no HFEs after 2020), Alternative B (long-term strategies B1 and B2; not more than one HFE every 2 years), and long-term strategies C3, E3, E5, and E6 (no HFEs). Based on modeled SMBI values, wetter hydrology is expected to transport more sediment downstream under all long-term strategies (Figure E-28).

E.4 LAKE DELTAS

The impact of sediment delta formation due to different alternatives must be inferred, because there are no models for this physical process. The following discussion and conclusions are based on existing data and on some of the modeling data for the sediment resource alternative analysis.

Lake deltas are formations that occur when sediments transported in high-energy riverine flow fall out of the water column as the river enters a lake and loses energy. The Colorado River, along with a number of smaller rivers (that used to be tributaries to the Colorado River but are now emptying directly into Lake Powell or Lake Mead) have deltas that form in locations determined by reservoir elevation. As the elevations of the lakes change, the locations of the deltas will also change (Figure E-29).

Lake Powell and Lake Mead deltas can be grouped into two categories: those deltas whose size and location would be affected by dam operations, and those whose location, but not size, would be affected by dam operations.

Only the Colorado River delta in Lake Mead can be affected in terms of both location and size; all other deltas' positions are affected by reservoir elevation (and their delta size is unaffected by dam operations). Using historical data from the GCMRC data portal (http://www.gcmrc.gov/discharge_qw_sediment/stations/GCDAMP), less than half (approximately 46%) of the suspended sand load reaching the gage above Diamond Creek (USGS gage 09404200) since October 2002 can be accounted for as suspended sand leaving Marble Canyon (USGS gage 09383100). The other half of the suspended sand reaching Diamond Creek comes from tributaries downstream of Marble Canyon, most notably the Little Colorado River. Figure E-30 compares the cumulative sand load above Diamond Creek (RM 225) to the cumulative sand load at Desert View (RM 61). This figure demonstrates that the amount of sediment passing RM 225 is approximately 22,000 ktons in the approximately 12.5-year time span since October 2002; this can be extrapolated to about 35,200 ktons of sand for a 20-year period (the same duration as the LTEMP analysis period). Similarly, the approximately 10,000 ktons of sand that have passed RM 61 since October 2002 can be extrapolated to approximately 16,200 ktons of sand for a 20-year period.

The mean SMBI resulting from the 20-year simulations indicates that there may be anywhere from 1,000 to 3,300 ktons of net loss in Marble Canyon sand, depending on the alternative. This decrease in Marble Canyon sand increases the amount of sand going past RM 61 by approximately 6% for Alternative A and 20% for Alternative F, as compared to historical data. Assuming all of the sand leaving Marble Canyon eventually passes Diamond Creek, these increased fluxes leaving Marble Canyon represent less than a 10% change in sand flux at RM 225 compared to the historical data.

The alternatives considered will have minimal impacts on the size of the Colorado River delta in Lake Mead, which is the only delta that could be affected in terms of size and location by Glen Canyon dam operations.

The positions of deltas in Lake Powell and Lake Mead are directly affected by reservoir elevation (Figure E-29). Changes to reservoir elevations are calculated in the CRSS model (Section 4.1 and Appendix D of this DEIS). The elevation of the lakes is compared to full pool elevations of 3,700 ft for Lake Powell and 1,229 ft for Lake Mead. The lake elevations from the alternatives are compared on a monthly basis and minima, means, and maxima were determined for the 63 simulations under each alternative. Figure E-31 presents the pool elevation for Lake Powell and Figure E-32 presents the pool elevation for Lake Mead. There is more variability related to differences in hydrology (compare the minimum and maximum for a given month) than there is related to different alternatives (compare colors across months). Pool elevations are ultimately controlled by regional hydrologic conditions and will not be affected by the alternatives. Alternative F is slightly different than the other alternatives because the monthly release volumes are low through winter. This small difference is not as pronounced as the variability due to annual inflow.

E.5 LIMITATIONS AND KNOWN ISSUES

E.5.1 Geographic Scope

The geographic scope of this DEIS includes the Colorado River from Glen Canyon Dam downstream, and west, to Lake Mead (Section 1.5.1 of this DEIS). This geographic scope in terms of Colorado River Mile is from RM 15 (Glen Canyon Dam; RM 0 is at Lees Ferry) to RM 347 (Hoover Dam). The numerical model upon which the sediment resource analysis is based extends from RM 0 to RM 87, although uncertainty in sand load from the Little Colorado River limited the analysis to Marble Canyon (RM 0 to RM 61).

E.5.2 Modeling Improvements

The average reallocation scheme (Section E.2.1.2) requires specification of a minimum flow rate about which fluctuations occur. The modeling for alternatives that use the average reallocation scheme and that allowed for daily fluctuations (Alternatives C, D, and E) have a fluctuation range specified at 5,000 cfs to 8,000 cfs. Due to differing up- and down-ramp rates, the average discharge is not 6,500 cfs but is closer to 6,521 cfs. Alternatives C and E used a specified flow rate of 6,500 cfs, but this error was found before modeling of Alternative D, and 6521 cfs was used for this alternative. Fixing the minimum flow rate for Alternatives C and E may result in a small adjustment to the results, but should not change relative rankings among alternatives.

Load-following curtailment was not implemented for all long-term strategies of Alternatives C and E. Fixing this issue is not expected to affect modeling results.

In a few cases during the modified sand budget modeling, sufficient water volume was identified to sustain an HFE; however, the water surface elevation in Lake Powell was below the minimum power pool intake elevation. This did not allow GTMax-Lite to develop refined hourly flows. In such cases, the sand budget model for the appropriate simulation(s) was run again without allowing an HFE to occur during the problem accounting period. A potential fix for this issue could result in the occurrence of a small HFE. This fix is expected to affect results for a given simulation; however, when considering the averaging across 63 simulations, the net effect is expected to be small.

Initial conditions for bed thickness and bed material size may not have been consistent between the first and second runs of the modified sand budget model for all long-term strategies. Wright et al. (2010) found that varying initial conditions by ±10% made less than a 7% difference in model results, so this fix is not expected to make a difference in alternative analysis.

One of the long-term strategies for Alternative D (D2) included sustained low flows for benthic invertebrate production (Section 2.2.4 of this DEIS). The set of months from which water is reallocated to support an HFE is not the same set of months when these sustained low flows are implemented, and implementing this in the model proved iterative and perhaps not as representative as it could be. Further modification to the sand budget model may improve the implementation of this flow management action; anticipated effects of this effort are unknown.

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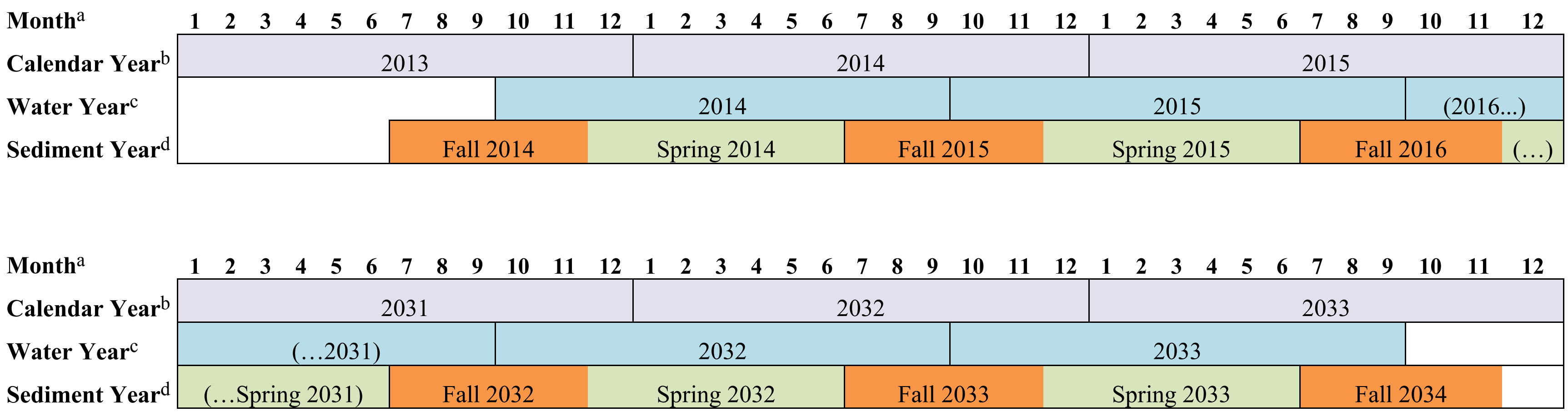


[a] 1 = January; 2 = February; 3 = March; 4 = April; 5 = May; 6 = June; 7 = July; 8 = August; 9 = September; 10 = October; 11 = November; 12 = December.

[b] Model simulations run for 21 calendar years.

[c] Analysis of alternatives covers 20 water years.

[d] Two accounting periods (spring/fall) per sediment year.

FIGURE E-1 Comparison of Calendar, Water, and Sediment Years

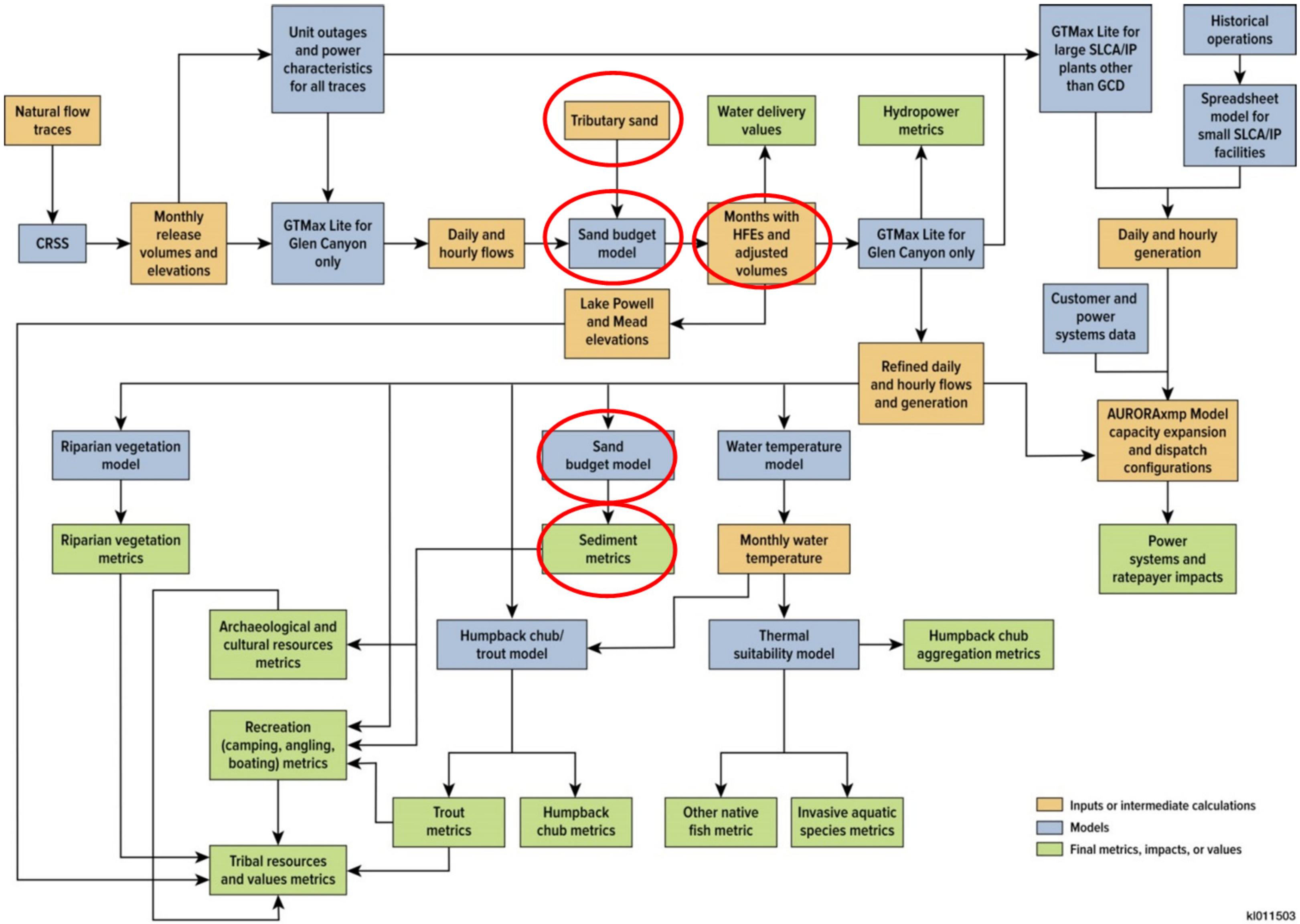


FIGURE E-2 Model Flow Diagram for Analyses Showing Inputs, Intermediate Calculations, and Output

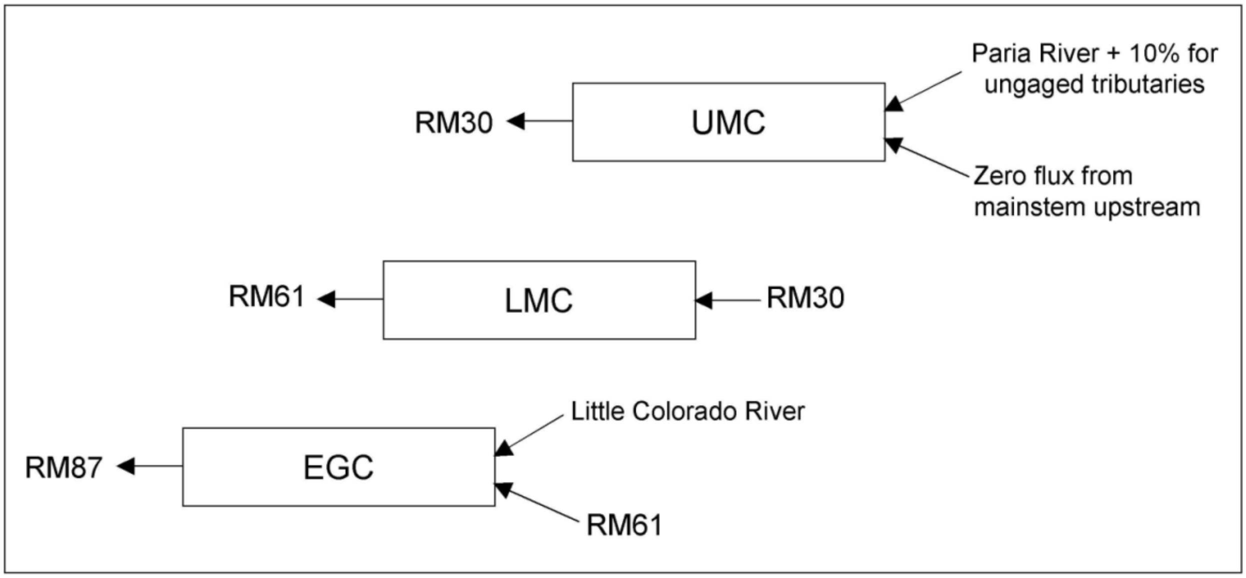


FIGURE E-3 Conceptual Schematic of the Sand Budget Model (UMC = Upper Marble Canyon; LMC = Lower Marble Canyon; EGC = Eastern Grand Canyon)

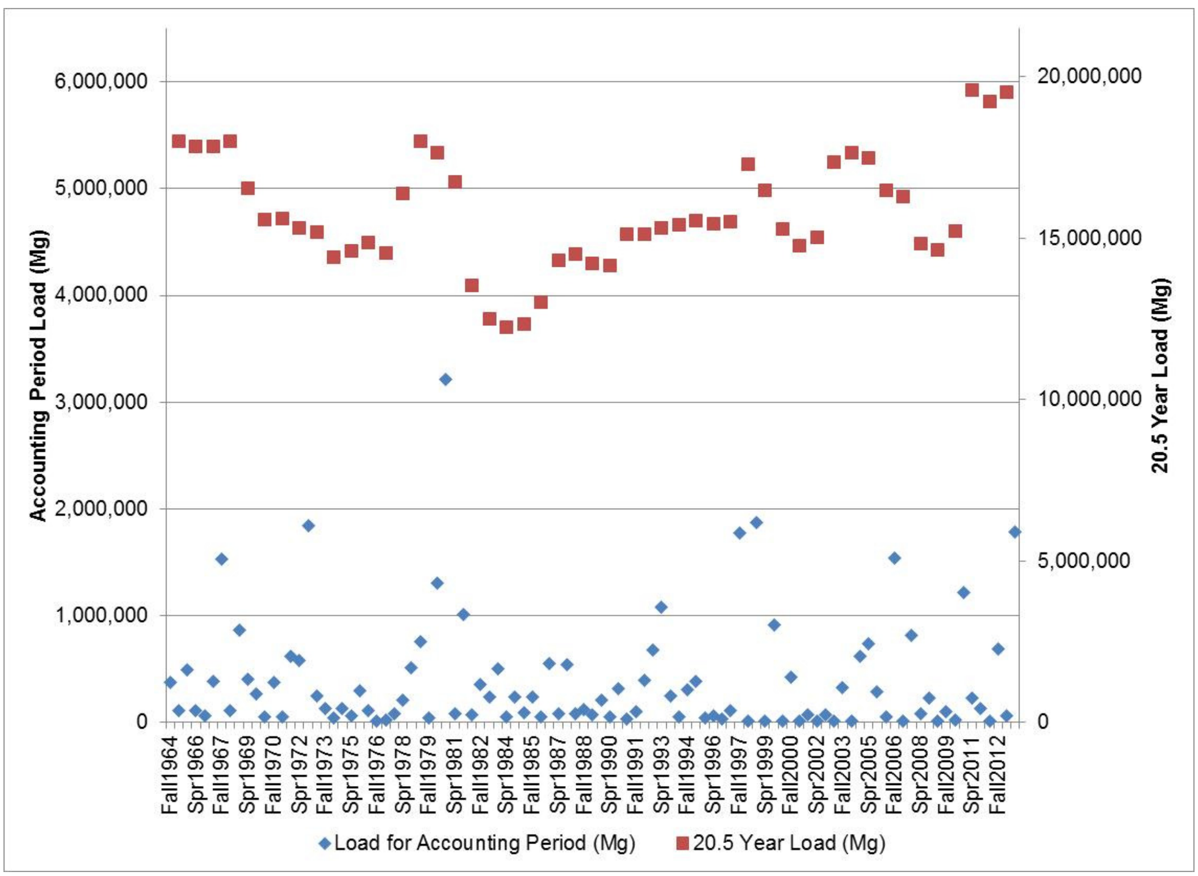


FIGURE E-4 Historical Paria Sediment Load per Accounting Period and the 20.5-year Load for the Trace That Begins in Each Fall Accounting Period

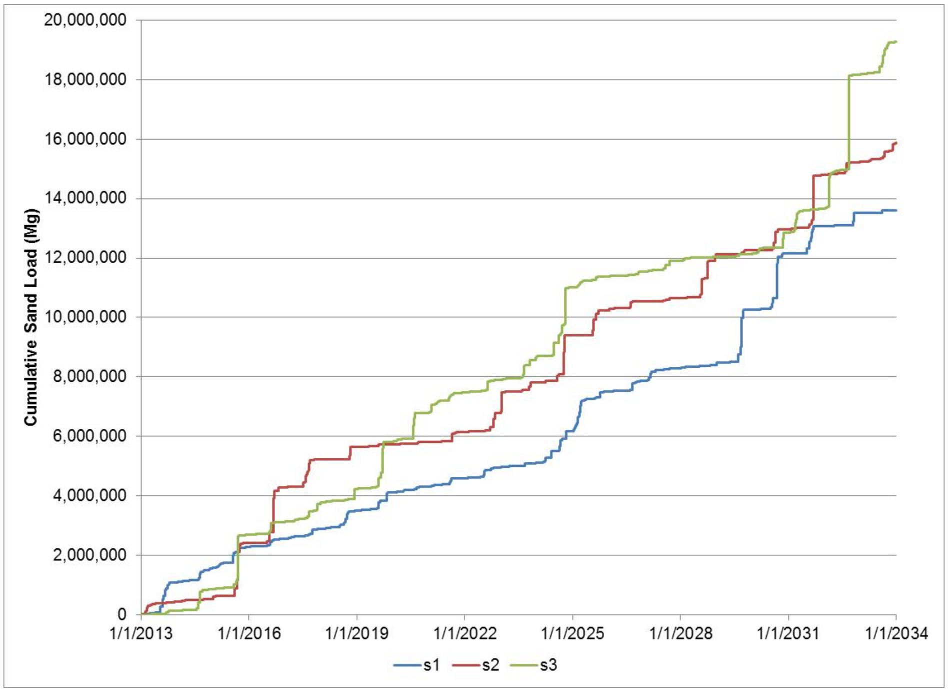


FIGURE E-5 Sediment Traces s1, s2, and s3 for the Paria River (presented as cumulative load) Used in the Modeling to Account for Uncertainty in Future Delivery

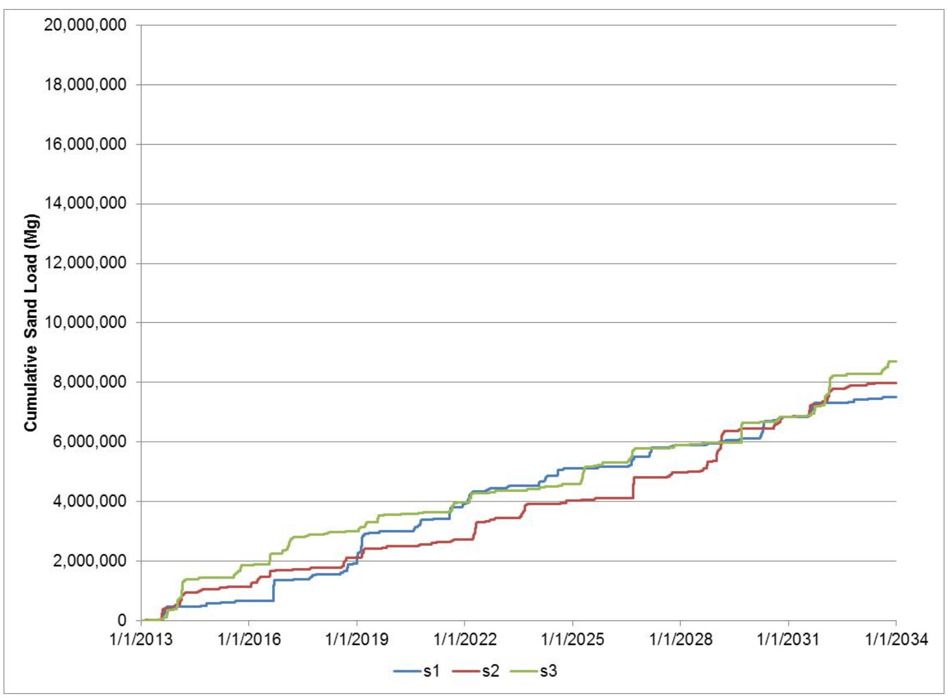


FIGURE E-6 Little Colorado River Sediment Traces (presented as cumulative loads) for s1, s2, and s3 Used in the Modeling to Account for Uncertainty in Future Delivery

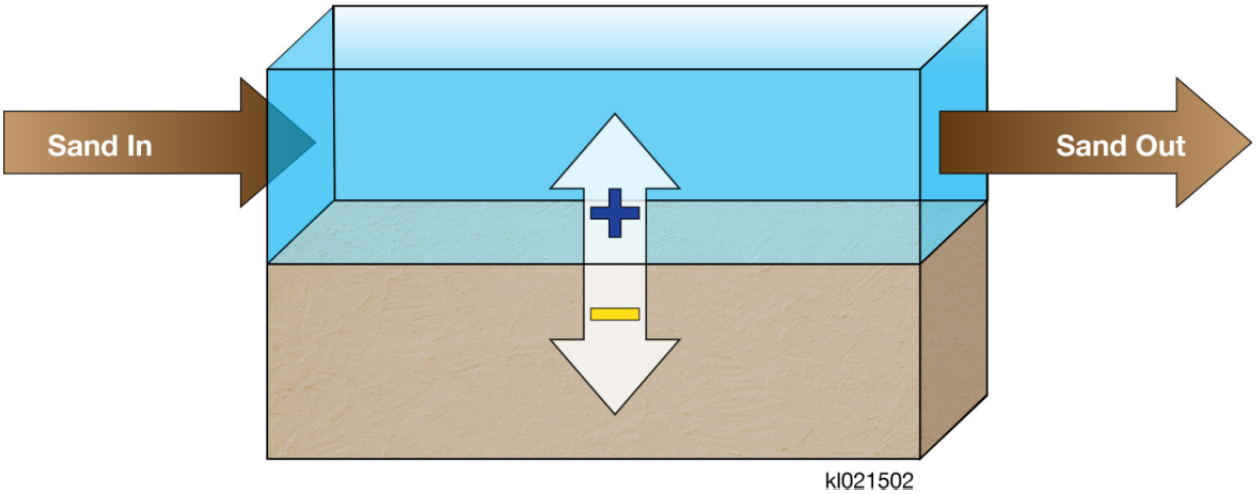


FIGURE E-7 Conceptual Representation of the Sand Mass Balance Index

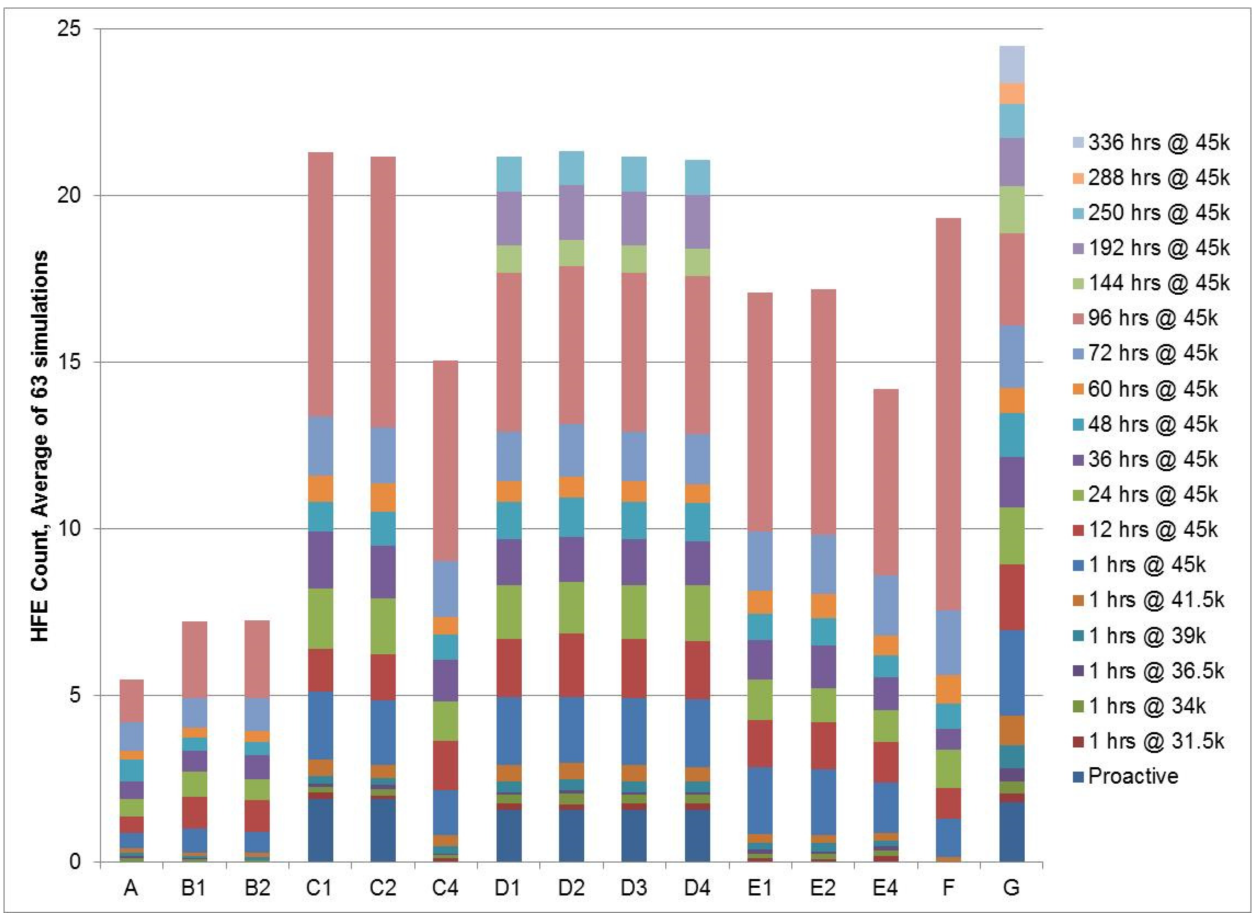


FIGURE E-8 Average Sediment and Hydrology Triggered HFE Count by Type for Each Long-Term Strategy (long-term strategies C3, E3, E5, and E6 by definition have no HFEs)

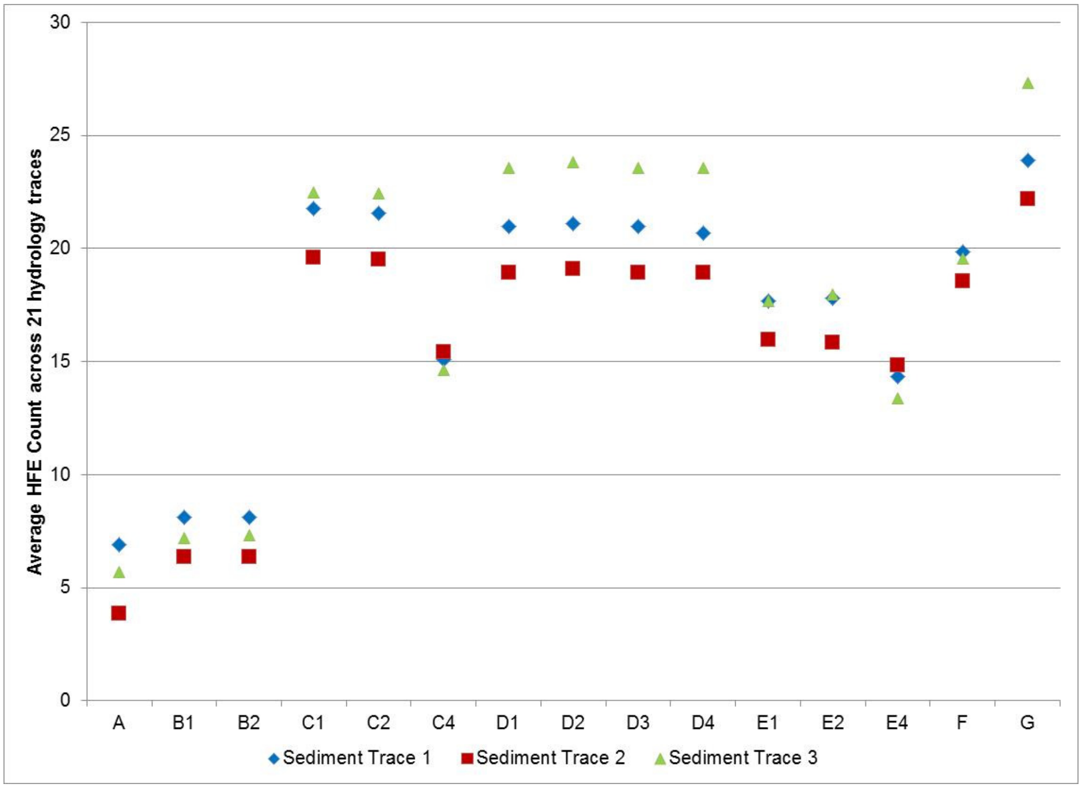
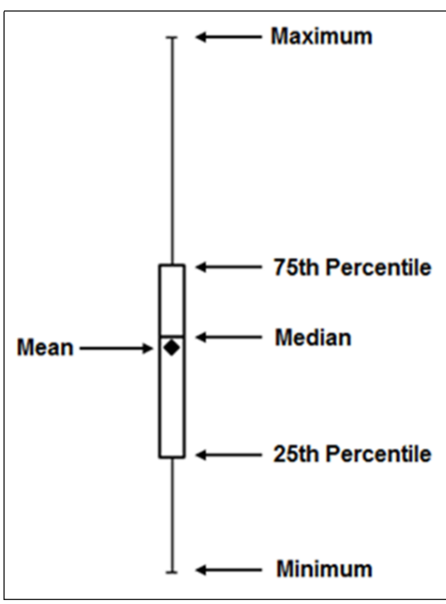


FIGURE E-9 Average HFE Count for Sediment Traces s1, s2, s3 for Each Long-Term Strategy (long-term strategies C3, E3, E5, and E6 by definition have no HFE)



Maximum: the single highest metric value out of the 63 simulations performed

75th Percentile: 75% (or ~47 of 63) of the simulations yield a metric value equal to or less than this

Median: also known as the 50th percentile; half of the simulations yield a metric value greater than this, and half yield a metric value less than this

Mean: arithmetic average of all 63 simulations

25th Percentile: 25% (or ~16 of 63) of the simulations yield a metric value equal to or less than this

Minimum: the single lowest metric value out of the 63 simulations performed

FIGURE E-10 Definition of the Statistics Represented by the Box and Whisker Plots Used in This Analysis

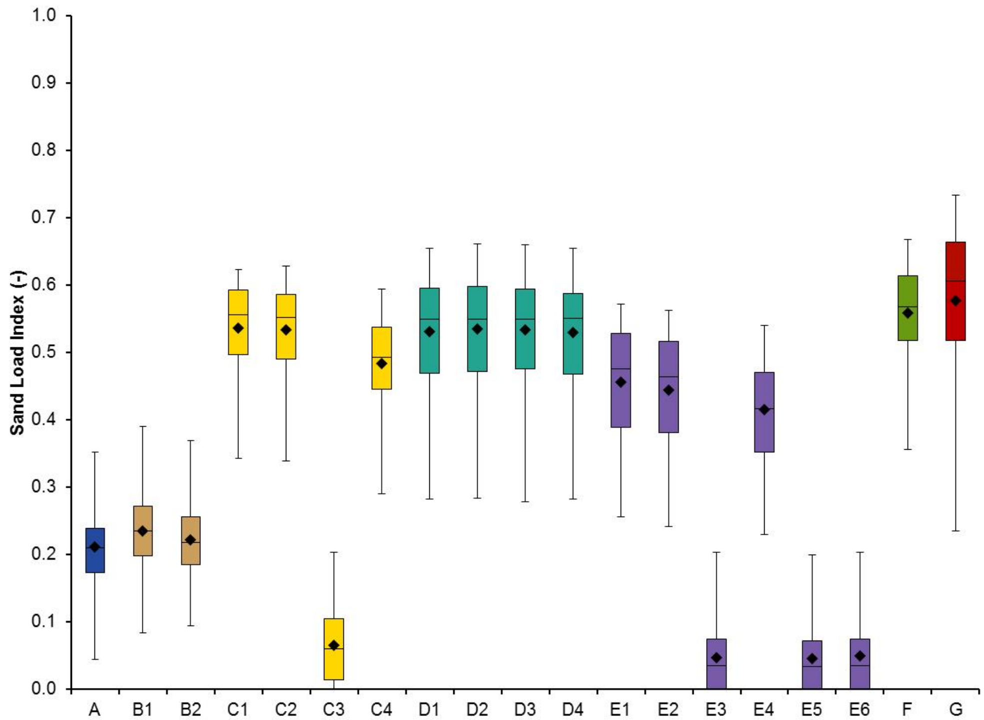


FIGURE E-11 Sand Load Index Statistics from 63 Simulations for Each Long-Term Strategy

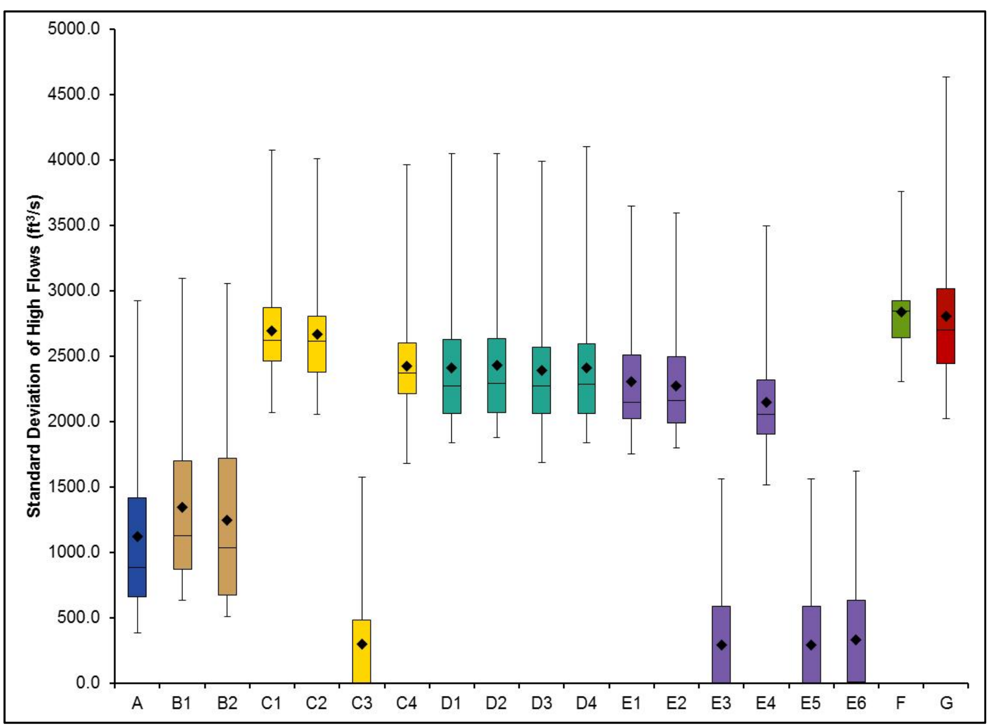


FIGURE E-12 Standard Deviation of High Flows Statistics from 63 Simulations for Each Long-Term Strategy

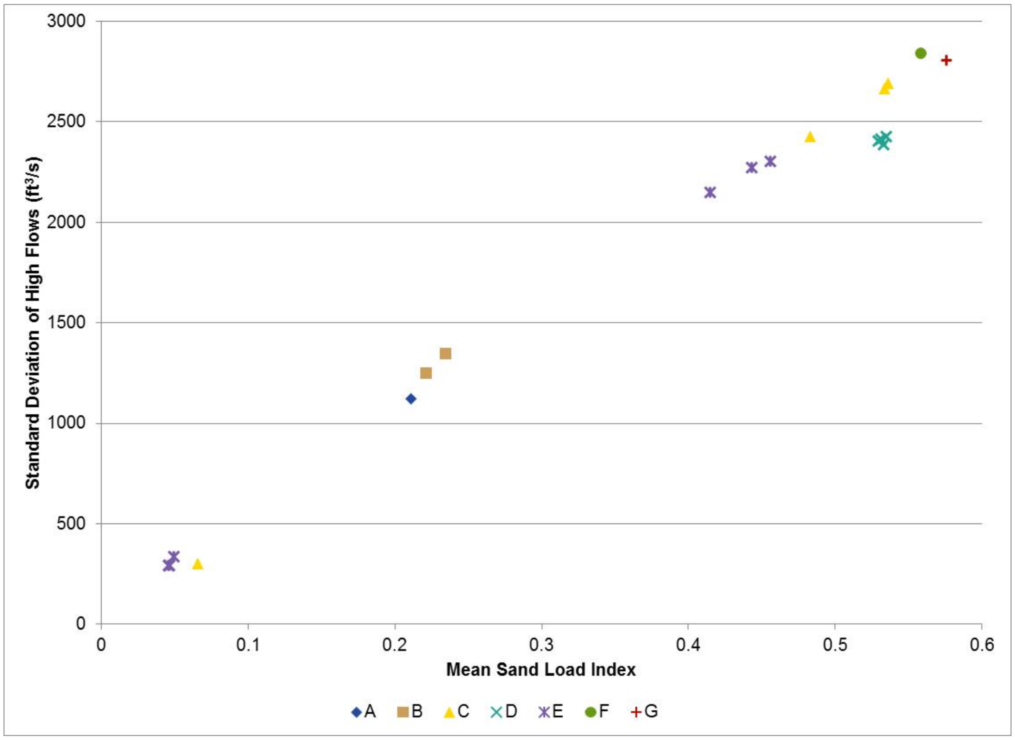


FIGURE E-13 Correlation between SDHF and SLI (r = 0.99, $P < 0.001$)

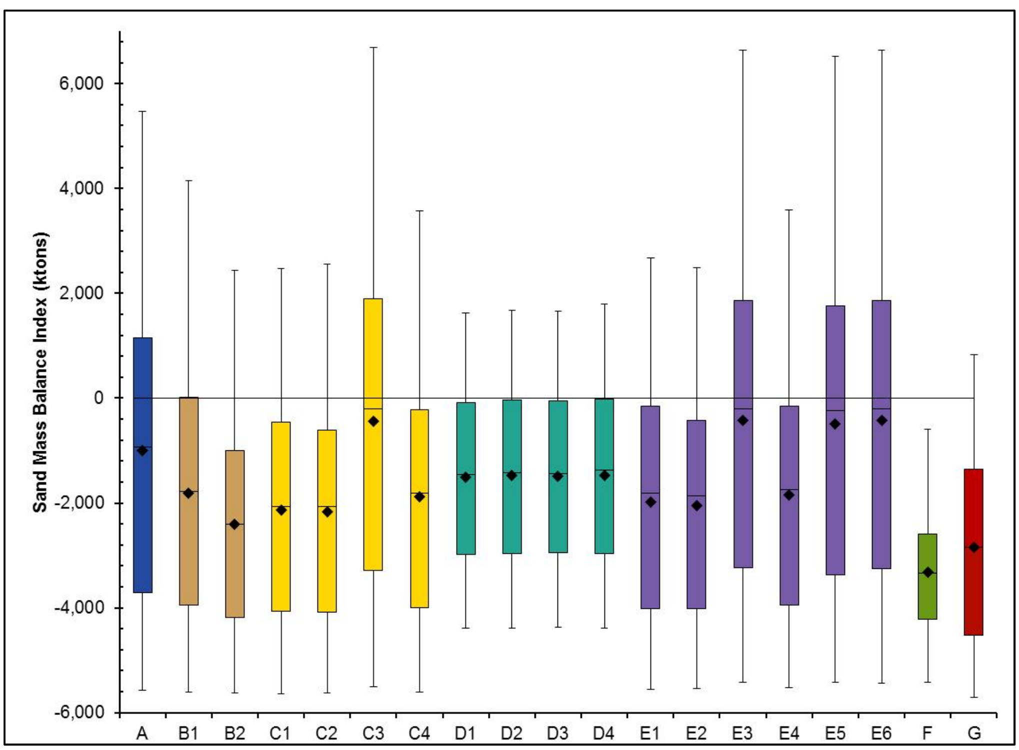


FIGURE E-14 Sand Mass Balance Index Statistics from 63 Simulations for Each Long-Term Strategy

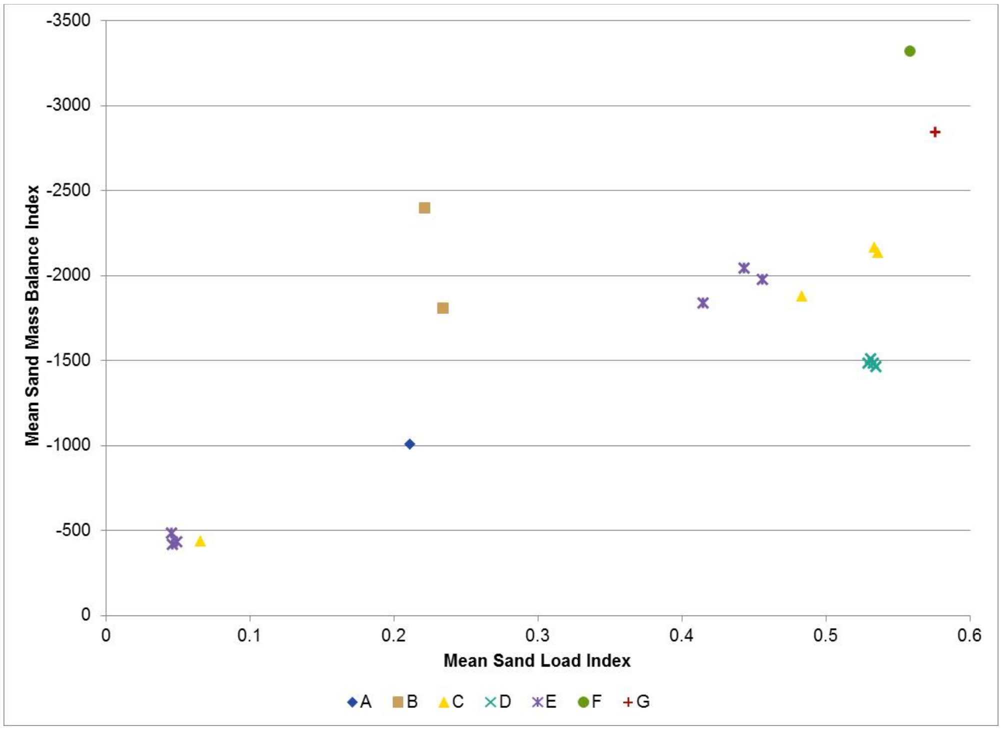


FIGURE E-15 Correlation between SMBI and SLI (r = 0.75, $P < 0.001$) (Note that the *y*-axis values are negative and in reverse order.)

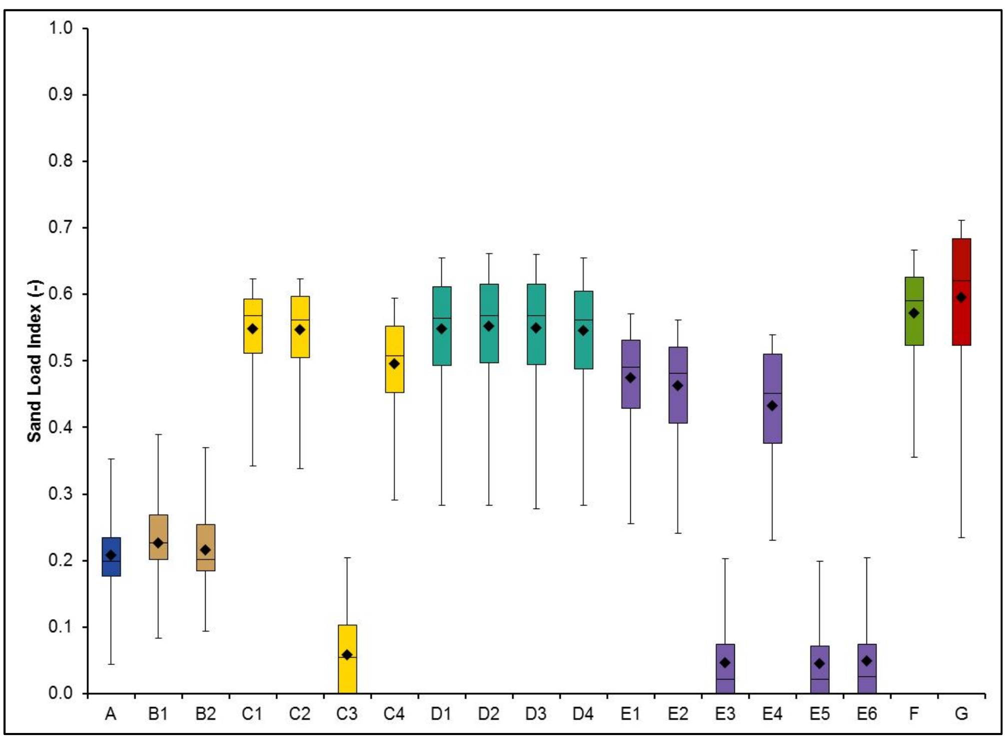


FIGURE E-16 Sand Load Index for Long-Term Strategies Using Climate Change Weights (Compare to Figure E-11, which uses historical weights.)

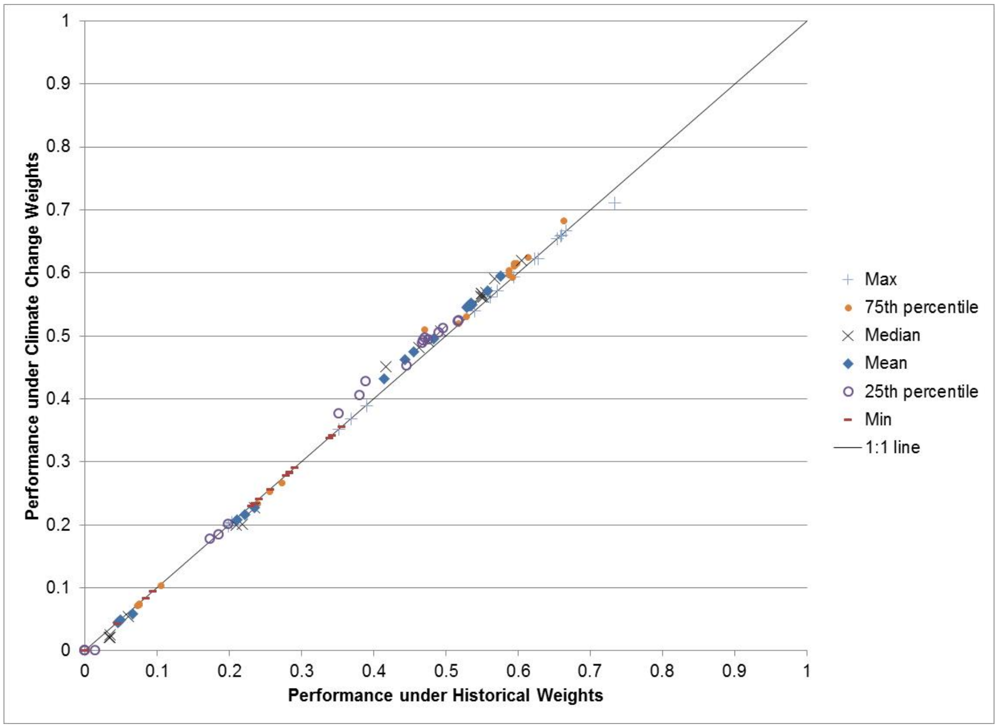


FIGURE E-17 Comparison of the Sand Load Index between Climate Change and Historical Weights

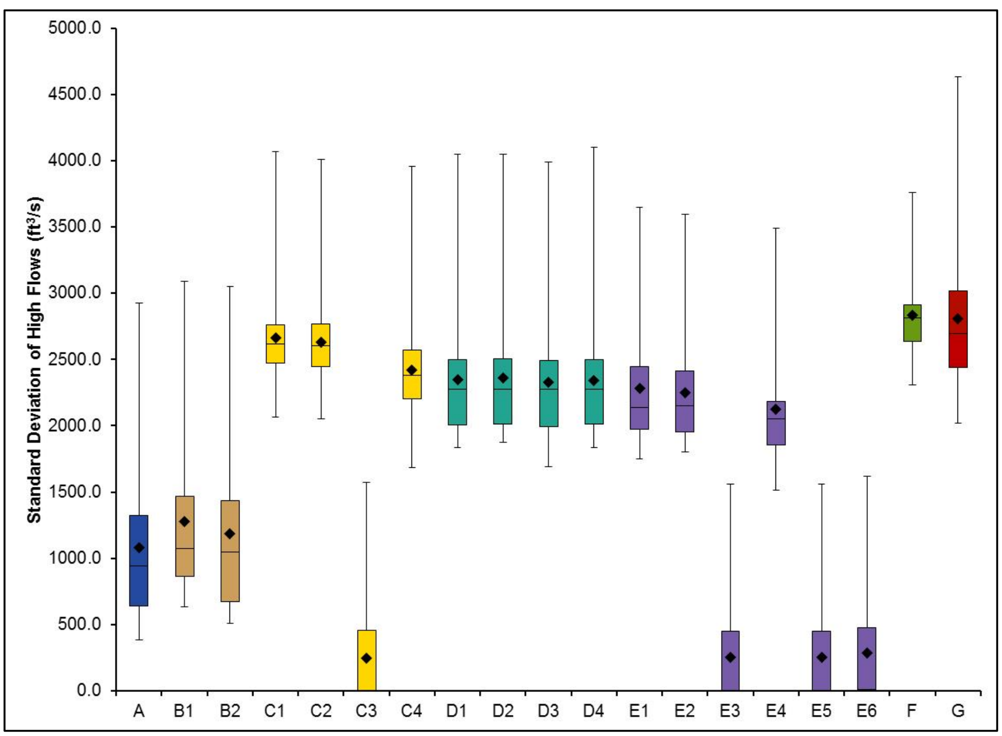


FIGURE E-18 Standard Deviation of High Flows Using Climate Change Weights (Compare to Figure E-12, which uses historical weights.)

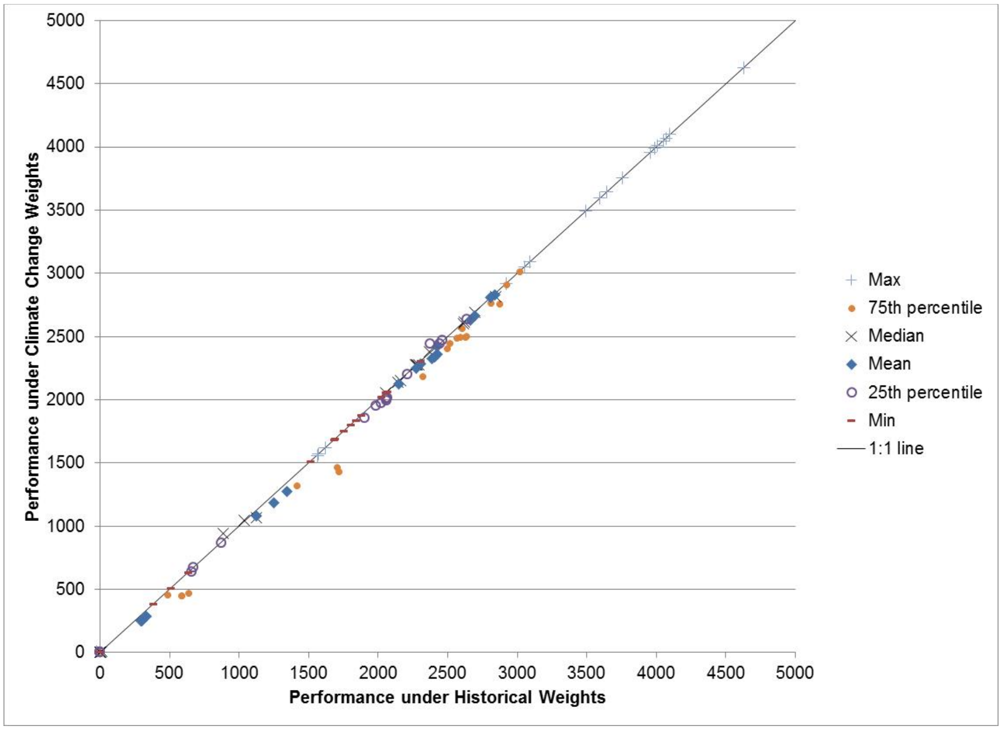


FIGURE E-19 Comparison of the Standard Deviation of High Flows between Climate Change and Historical Weights

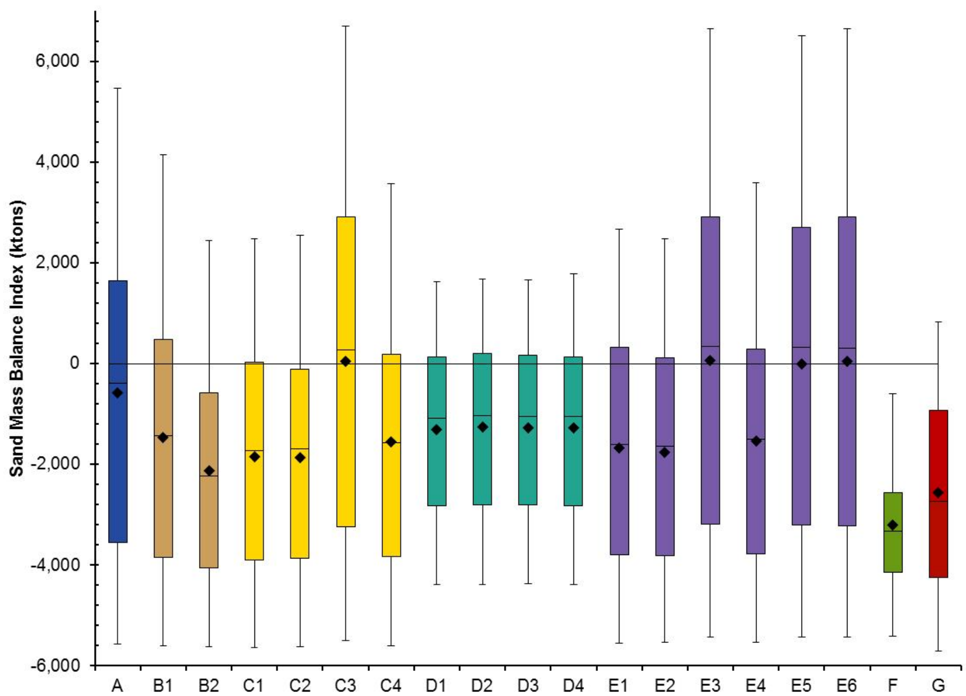


FIGURE E-20 Sand Mass Balance Index Using Climate Change Weights (Compare to Figure E-14, which uses historical weights.)

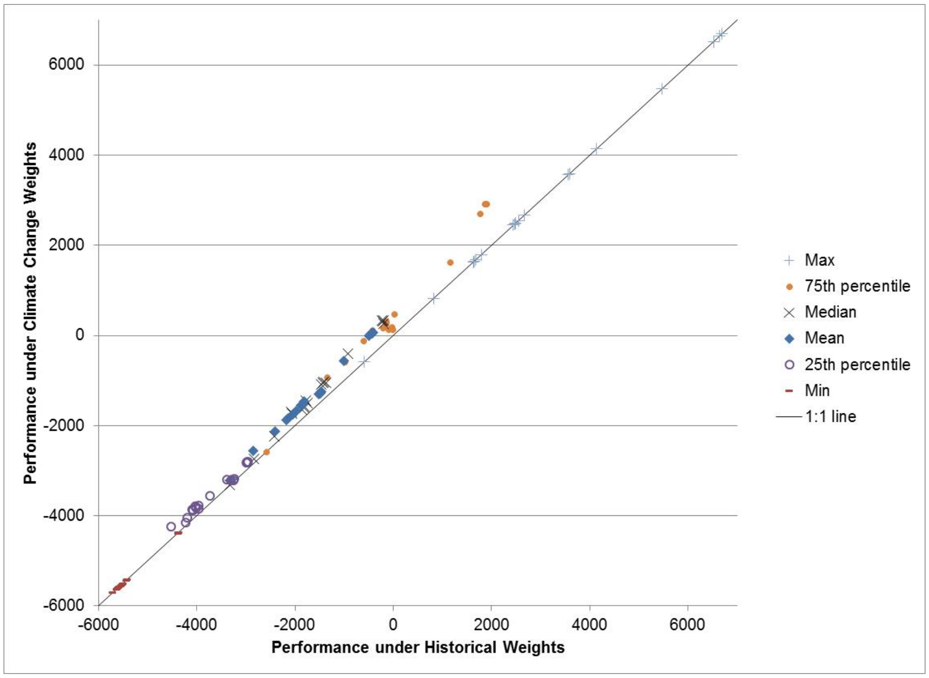


FIGURE E-21 Comparison of the Sand Mass Balance Index between Climate Change and Historical Weights

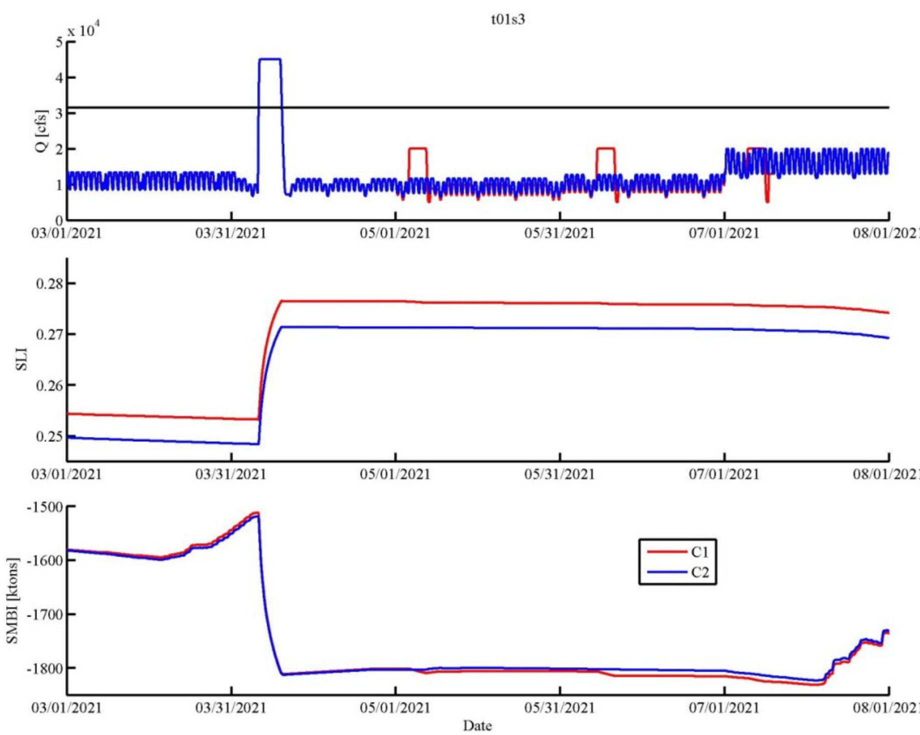


FIGURE E-22 Comparison of Long-Term Strategies C1 and C2 for Hydrology Trace 1, Sediment Trace 3 (TMF flows have very little effect on SLI or SMBI.)

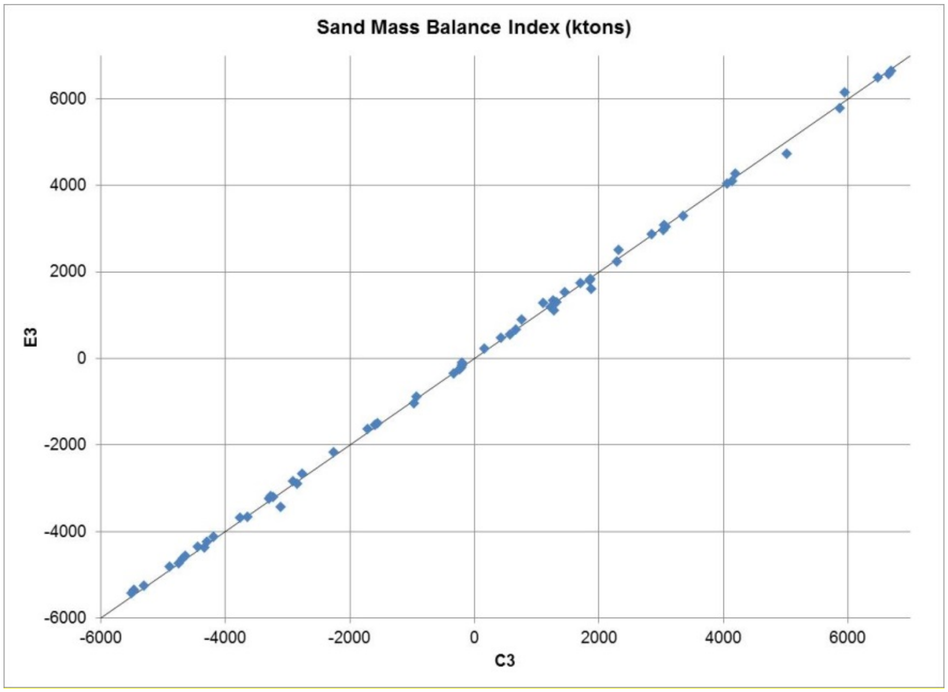


FIGURE E-23 SMBI for Alternative E Plotted against Alternative C (The combination of intervening flows and monthly volumes yields no difference in SMBI.)

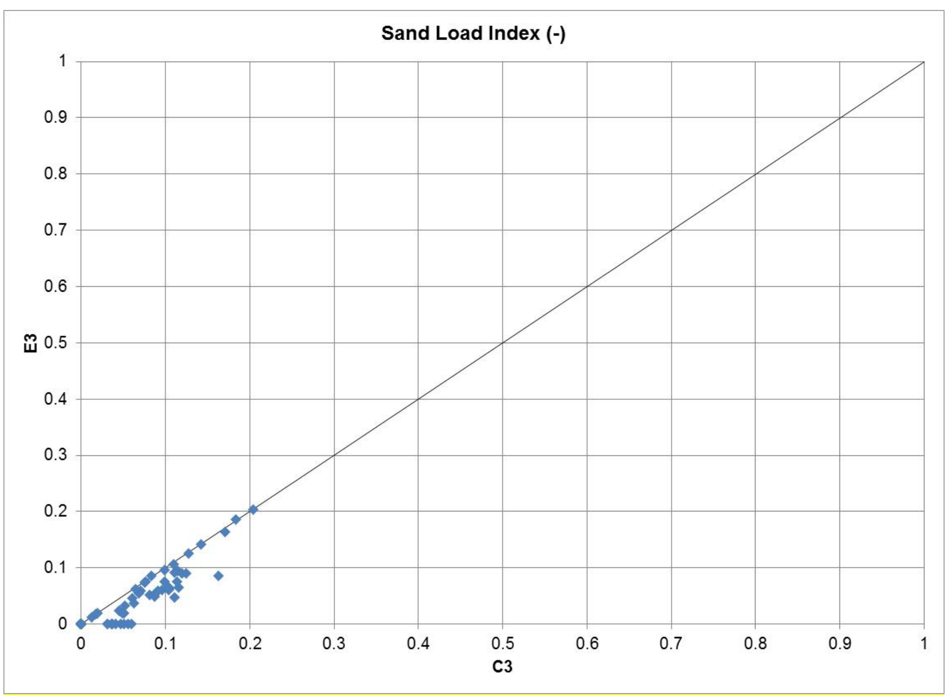


FIGURE E-24 SLI for Alternative E Plotted against Alternative C (The combination of intervening flows and monthly volumes yields small differences in SLI.)

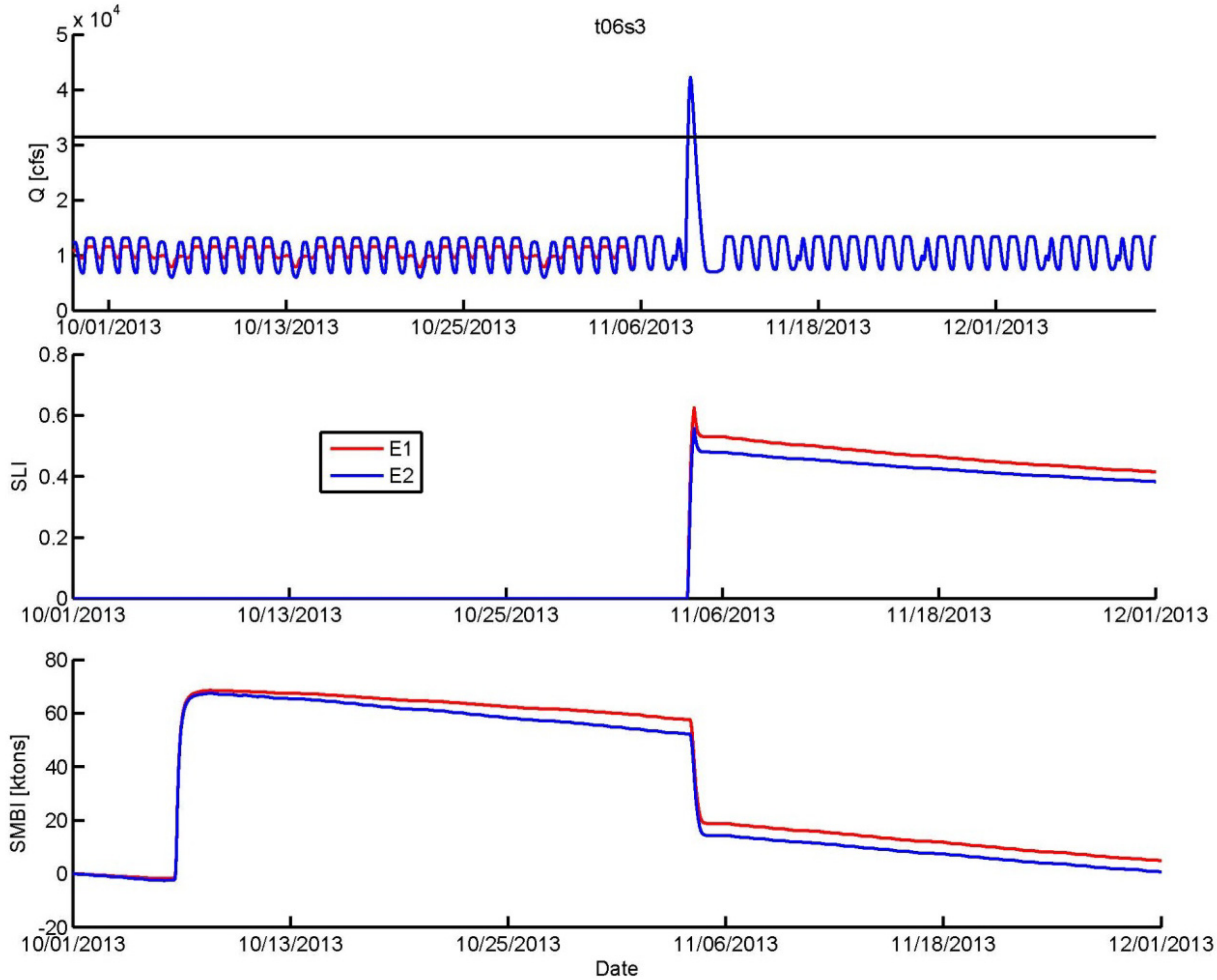


FIGURE E-25 Load-Following Curtailment Effects on SLI and SMBI (Although small effects are noticeable for the month after an HFE, by the end of the calendar year there is no difference in SLI and the difference in SMBI is 9 ktons.)

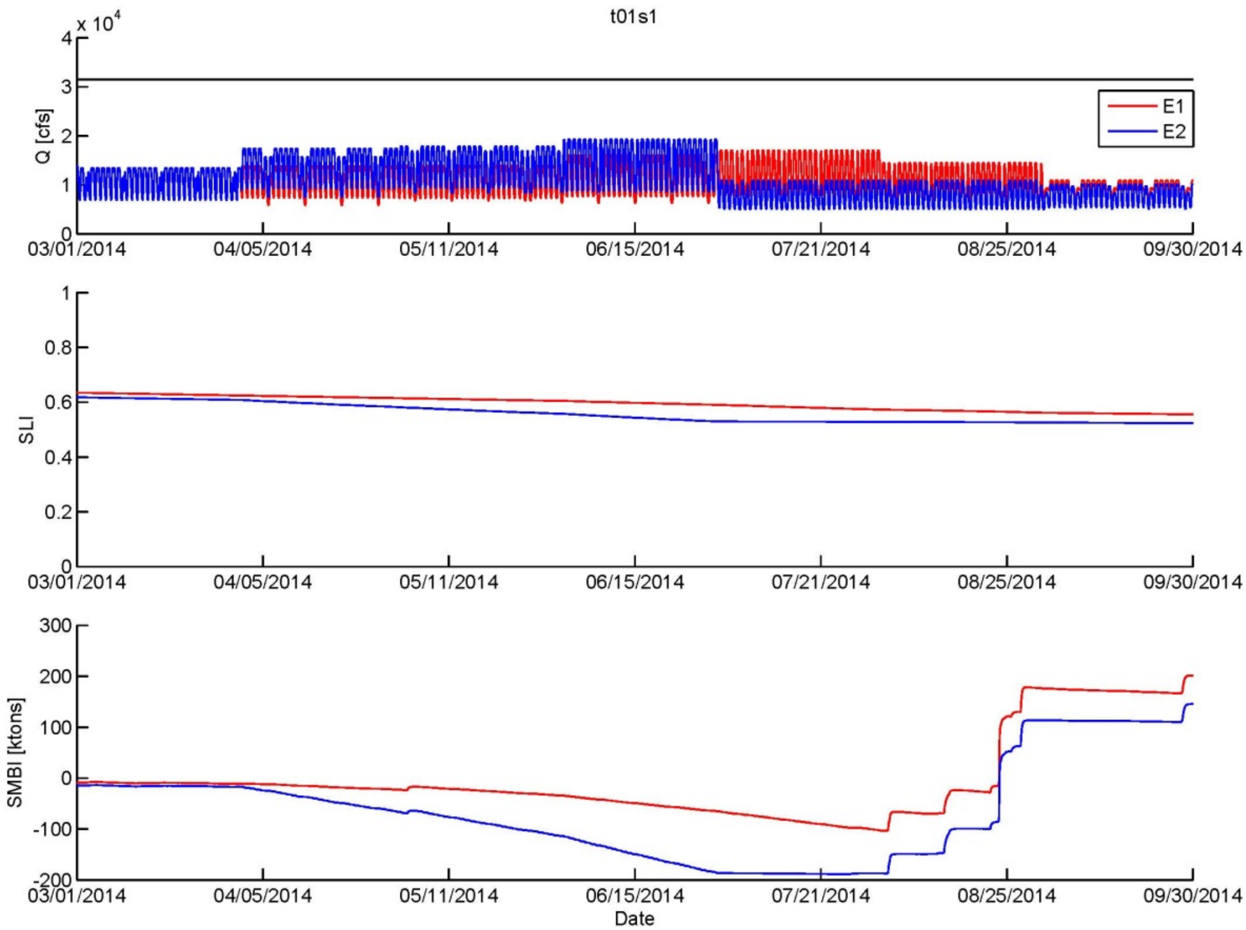


FIGURE E-26 Low Summer Flows for WY 2014, Hydrology Trace 1, Sediment Trace 1 (Long-term strategy E2 has low summer flows starting in July; this necessitates higher flows in April–June. Both SLI and SMBI are higher for alternative strategies without low summer flows [long-term strategy E1] than for those with low summer flows [long-term strategy E2].)

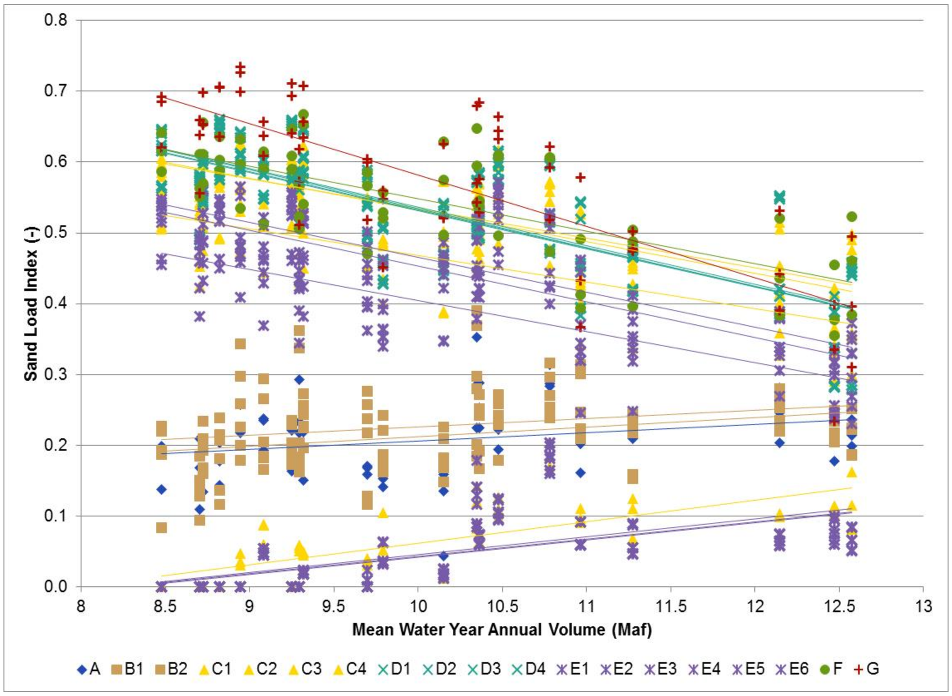


FIGURE E-27 Hydrology Impacts on the Sand Load Index (Wetter hydrological conditions tend to reduce SLI for long-term strategies without defined restriction on the number of HFEs that can be triggered [C1, C2, D1, D2, D3, D4, E1, E2, F, G]. Wetter hydrological conditions tend to increase SLI for long-term strategies with defined restrictions on the number of HFEs that can be triggered [A, B1, B2, C3, C4, E3, E4, E5, E6].)

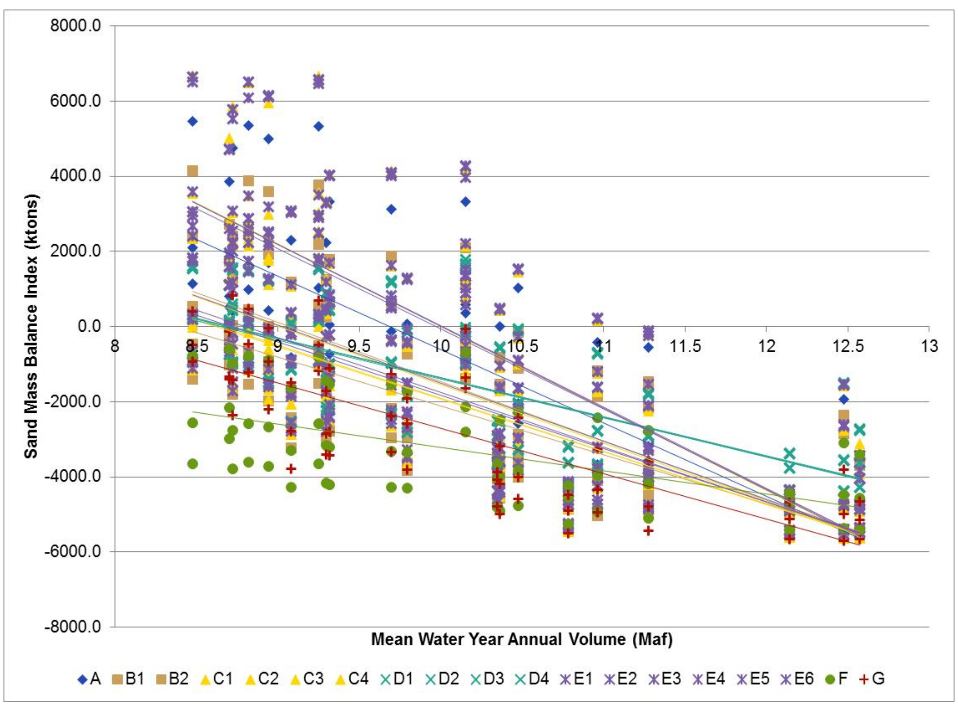


FIGURE E-28 Hydrology Impacts on the Sand Mass Balance Index (Wetter hydrological conditions create lower Sand Mass Balance Index values.)

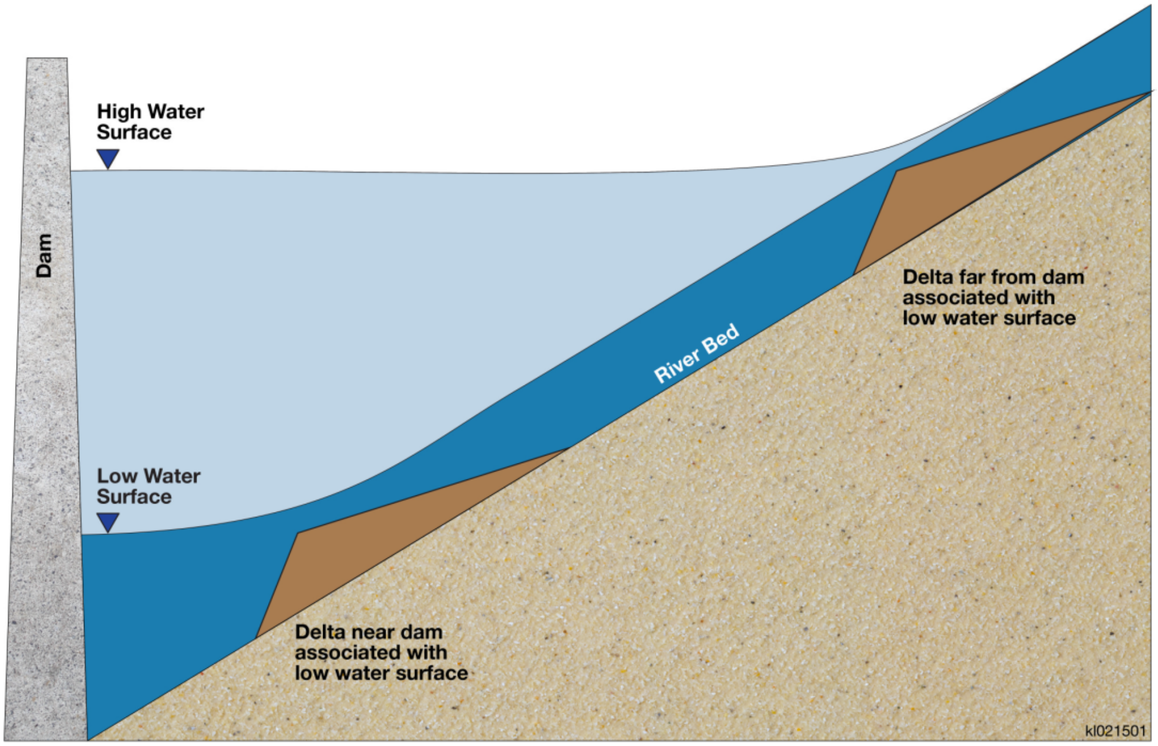


FIGURE E-29 Conceptual Diagram of Water Surface Elevation Affecting Delta Location

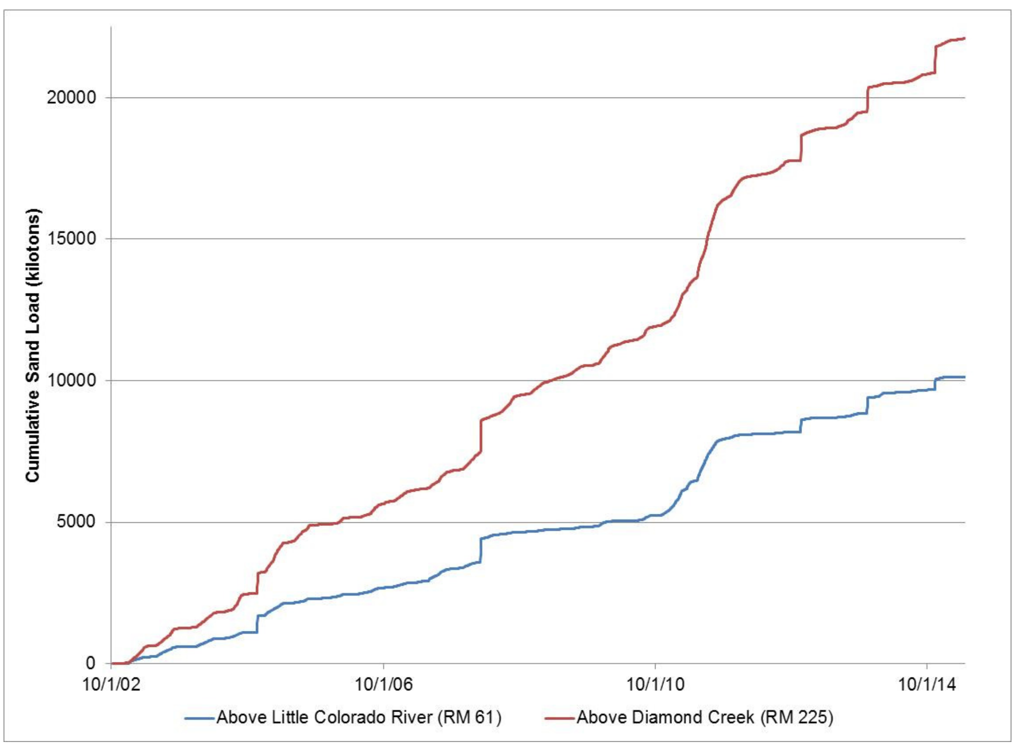


FIGURE E-30 Historical Cumulative Sand Load Leaving Marble Canyon (RM 61) and Reaching the Gage above Diamond Creek (RM 225) (Source: GCMRC 2015)

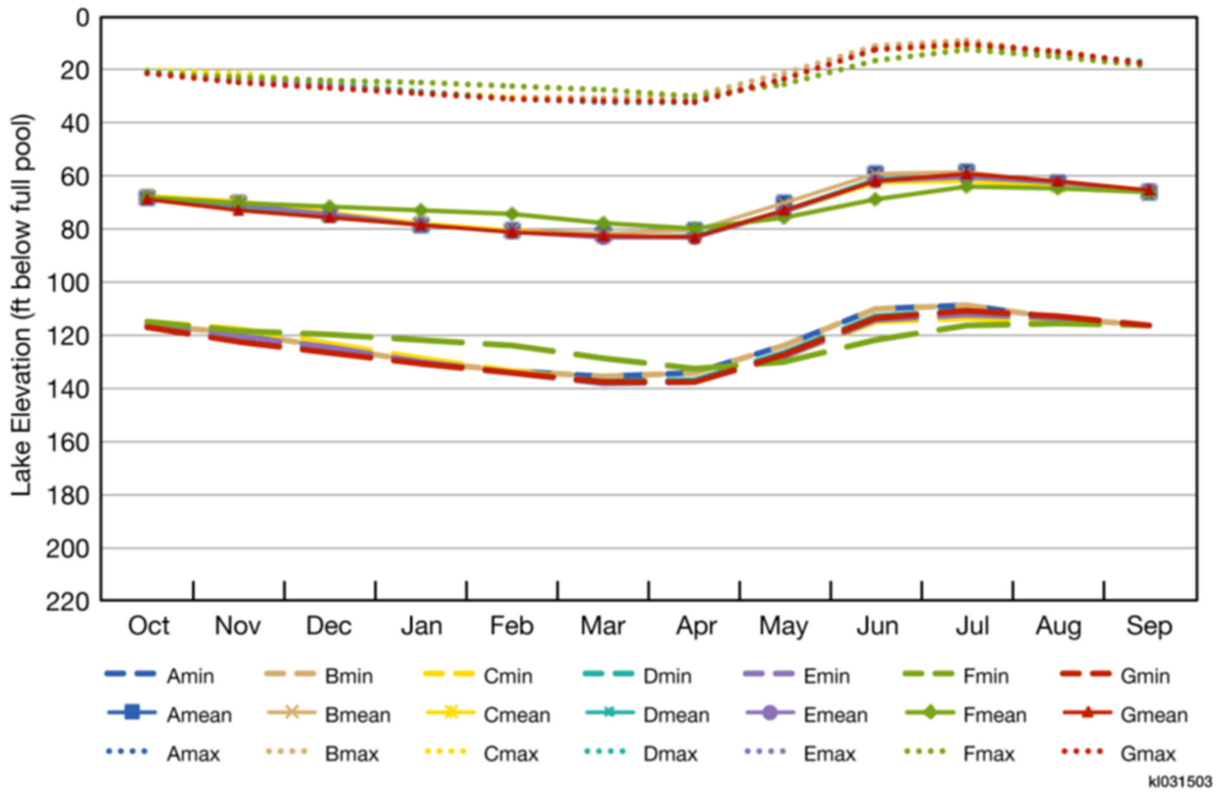


FIGURE E-31 Hydrology Impacts of Lake Powell Pool Elevations by Month across Alternatives

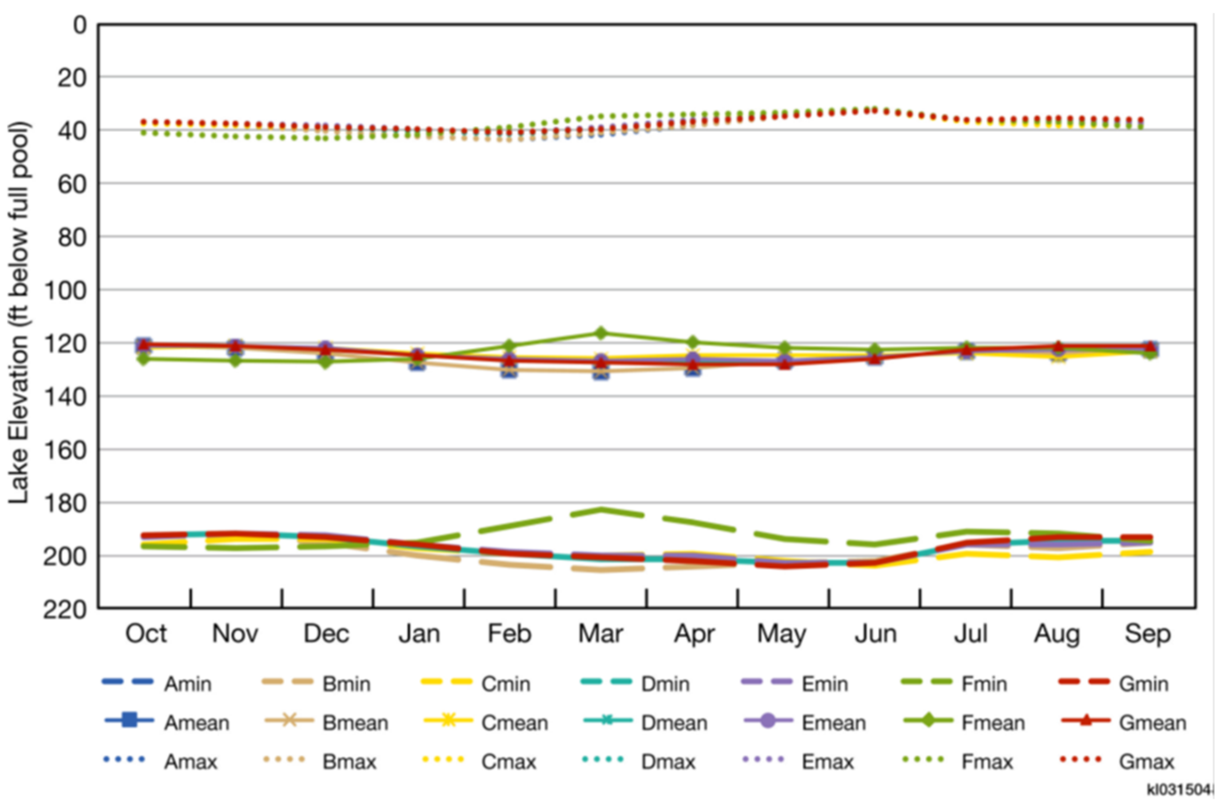


FIGURE E-32 Hydrology Impacts of Lake Mead Pool Elevations by Month across Alternatives

TABLE E-1 Sources for Historical Tributary Sediment Load Data

Tributary	Period of Record, by Source: Topping (2014)	Period of Record, by Source: GCMRC (2015)	Record Length
Paria River	10/1/1963 to 10/1/1996	10/1/1996 to 1/1/2014	50.3 years
Little Colorado River	10/1/1994 to 3/27/2013		18.5 years

TABLE E-2 Historical Periods Used for Paria Sediment Traces s1, s2, and s3

Sediment Trace	Sediment Accounting Periods	Simulation Period
s1	Fall 1981–Fall 2001	1/1/1981–12/31/2001
s2	Fall 1995–Fall 2013 : Spring 1964–Fall 1965	1/1/1995–11/30/2013 : 12/1/1963–12/31/1965
s3	Fall 2011–Fall 2013 : Spring 1964–Fall 1981	1/1/2011–11/30/2013 : 12/1/1963–12/31/1981

TABLE E-3 Historical Periods Used for Little Colorado River Sediment Traces s1, s2, and s3

Sediment Trace	Simulation Period
s1	1/1/1999–12/31/2012 : 1/1/1995–12/31/2001
s2	1/1/2007–12/31/2012 : 1/1/1995–12/31/2009
s3	1/1/2004–12/31/2012 : 1/1/1995–12/31/2006

TABLE E-4 List of HFEs Available for Sediment-Triggered Events (fall and spring)

HFE ID	Peak Discharge (cfs)	Duration at Peak (hours)
A	45,000	336
B	45,000	288
C	45,000	240 (Alternative G) 250 (Alternative D)
D	45,000	192
E	45,000	144
1	45,000	96
2	45,000	72
3	45,000	60
4	45,000	48
5	45,000	36
6	45,000	24
7	45,000	12
8	45,000	1
9	41,500	1
10	39,000	1
11	36,500	1
12	34,000	1
13	31,500	1

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APPENDIX F:

AQUATIC RESOURCES TECHNICAL INFORMATION AND ANALYSIS

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APPENDIX F:

AQUATIC RESOURCES TECHNICAL INFORMATION AND ANALYSIS

F.1 INTRODUCTION

This technical appendix provides information pertaining to analyses of effects on aquatic ecological resources for the Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) Draft Environmental Impact Statement (DEIS), including the aquatic food base, native and nonnative fishes, and fish parasites. It is intended to supplement the information presented in Sections 3.5 and 4.5 of the DEIS.

Methods used to evaluate resources, including modeling methods, are described and results regarding effects of alternatives and associated long-term strategies are presented. Analysis of effects on the aquatic food base is based upon a review of literature pertaining to past studies and extrapolation of those results to qualitatively evaluate effects of alternatives and the associated long-term strategies. The evaluation of impacts on rainbow trout (*Oncorhynchus mykiss*), endangered humpback chub (*Gila cypha*), other native fish, nonnative fish, and fish parasites is based upon reviews of the scientific literature and upon the evaluation of performance metrics that were developed for the LTEMP assessment process. The values for the performance metrics were calculated using models developed to examine effects of alternatives on the various aquatic resources.

The potential effects of six action alternatives are compared to the no action alternative (Alternative A), which describes how the dam is currently operated. Operations under Alternative A employ a release pattern established in the 1996 Record of Decision (ROD) (Reclamation 1996) associated with the 1995 Environmental Impact Statement (EIS) on operations of Glen Canyon Dam (Reclamation 1995). This operational release pattern, referred to as Modified Low Fluctuating Flows, moderated the releases relative to operations practiced in the 1960s through 1980s. As described in Chapter 2 of the DEIS, Alternative A also includes various operational decisions and non-flow actions that have been established since the 1996 ROD.

Some of the alternatives under consideration in the DEIS (especially Alternatives C, D, and E) are complex experimental or adaptive designs. These alternatives prescribe different management interventions depending on resource conditions. Various condition-dependent triggers govern the implementation of experiments. To understand effects of alternatives that incorporate multiple adaptive components, especially components that might be considered experimental, the complex alternatives were decomposed into nineteen versions referred to as long-term strategies, with specific experimental elements included or excluded in each long-term strategy. Table 4.1-1 identifies the experimental elements included in each of the long-term strategies associated with the LTEMP alternatives. Descriptions of each alternative, including the elements included in the long-term strategies, are presented in Sections 2.2 and 4.1 of the DEIS. Modeling to evaluate potential effects on aquatic resources was conducted similarly for each long-term strategy and results were compared using various performance metrics to evaluate how inclusion of experimental elements as part of an alternative affected the modeled outcome for the resources of concern. As discussed in Section 4.1 of the DEIS, the long-term strategies used to represent the alternatives in Section 4.5 are A, B1, C1, D4, E1, F, and G.

A full range of potential hydrologic and sediment conditions were modeled for a 20-year period (water years 2013–2033) that represented the 20 years of the LTEMP. Twenty-one potential Lake Powell inflow scenarios (known as hydrology traces) for the 20-year LTEMP period were sampled from the 105-year historic record (water years 1906 to 2010) using the Index Sequential Method and selecting every fifth sequence of 20 years. Using this approach, the first 20-year period considered was 1906–1925, the second was 1911–1930, and so forth. As the start of traces reach the end of the historic record, the years needed to complete a 20-year period are obtained by wrapping back to the beginning of the historical record. For instance, the trace beginning in 1996 consists of the years 1996–2010 and 1906–1910, in that order. This method produced 21 hydrology traces for analysis that represented a range of possible conditions from dry to wet.

In addition to these 21 hydrology traces, three 20-year sequences of sediment inputs from the Paria River sediment record (water years 1964–2013) were analyzed that represented low (water years 1982 to 2001), medium (water years 1996 to 1965), and high (water years 2012 to 1981) sediment input conditions. In combination, the 21 hydrology traces and 3 sediment traces resulted in an analysis that considered 63 possible hydrology-sediment conditions for each alternative and long-term strategy.

Section F.2 of this appendix describes analyses conducted to evaluate impacts of alternatives on the aquatic food base. Section F.3 presents methods, results, and conclusions from modeling conducted to evaluate population-level effects of alternatives on rainbow trout and humpback chub. Section F.4 presents methods, results, and conclusions for modeling conducted to evaluate how alternatives would affect the suitability of mainstem water temperatures for sustaining populations of humpback chub and other native fish species, nonnative fish species, and fish parasites.

F.2 AQUATIC FOOD BASE ASSESSMENT

This section provides information on flow and temperature effects of LTEMP alternatives on the aquatic food base. It serves as the basis for descriptions and conclusions provided in Sections 3.5.1 and 4.5 of this DEIS.

F.2.1 Description of the Aquatic Food Base Downstream from Glen Canyon Dam

Determining the impacts of LTEMP alternatives on the aquatic food base requires an evaluation of changes in the aquatic food base from pre-dam years through various post-dam operations, changes in the food base that occur with increasing distance from the dam, and the effects of intentional and unintentional species introductions. The following discussion provides this information and supplements the aquatic food base information presented in Section 3.5.1.

F.2.1.1 The Aquatic Food Base Prior to Construction of Glen Canyon Dam

Prior to the construction of Glen Canyon Dam, the productivity of the Colorado River was low due to scouring and high turbidity levels that limited the colonization and growth of benthic macroalgae and invertebrates (Woodbury 1959; Stevens et al. 1997; Ward et al. 1986). Generally, the more productive habitats for algae and invertebrates occurred at the lower edge of deltas formed at the mouths of tributaries, on and behind boulders, and on woody debris carried by flood waters (Woodbury 1959). A pre-dam survey of 171 mi of the Colorado River between Dirty Devil River, Utah, and Lees Ferry, Arizona (collections made along the banks of the Colorado River and in tributaries or side canyons), included 28 species of green algae, 5 species of cyanobacteria, 20 species of diatoms, and 91 species of insects including mayflies, dragonflies, true bugs, fishflies, caddisflies, aquatic snout moths, beetles, and true flies (Woodbury 1959). Sixteen insect species were collected from sites along the river bank while 77 species were collected from tributary streams. From a sample of fish stomachs, it appeared that organisms derived from tributaries and terrestrial habitats played an important role in the diet of river fishes (Woodbury 1959). Pre-dam reports of invasive aquatic food base species in the Grand Canyon are limited. In 1932, 50,000 amphipods (*Gammarus lacustris*) were introduced into Bright Angel Creek. They apparently washed into the mainstem of the Colorado River where they became abundant (Carothers and Minckley 1981), particularly within the Glen Canyon reach, where they are associated with *Cladophora* beds (Blinn and Cole 1991; Blinn et al. 1992; Hardwick et al. 1992).

Stanford and Ward (1986) suggested that the lower Green and Colorado Rivers in Canyonlands National Park, Utah, may provide the best examples of the pre-regulated Colorado River, as these reaches retain similar hydrographs to pre-dam conditions and are the farthest downstream from the large dams in the upper Colorado River basin. High suspended sediment concentrations limited the growth of primary producers; thus, the primary carbon source for benthic invertebrates was terrestrial organic matter. The invertebrate community was composed of 49 taxa, mostly mayflies, caddisflies, and true flies. Stoneflies and dragonflies comprised a smaller portion of the community (Haden et al. 2003).

F.2.1.2 The Aquatic Food Base of the Colorado River Downstream from Glen Canyon Dam

Section 3.5.1 of the DEIS provides an overview of the aquatic food base of the mainstem of the Colorado River following installation of Glen Canyon Dam. The following supplements that information. Glen Canyon Dam altered the primary carbon source from terrestrial (e.g., leaf litter) to aquatic (e.g., algae and detritus), the temperature regime from seasonally warm to stenothermically cool, and discharge patterns from low daily variations to high daily variations (Benenati et al. 2002). Nevertheless, riparian and upland vegetation still contribute energy to the impounded river system, particularly during flood events (Blinn et al. 1998, 1999). The large quantity of driftwood that occurred in the pre-dam river is now replaced by lower quantities of woody debris derived from tributaries during floods, or from occasional scouring flows of the vegetated post-dam shoreline (Stevens et al. 1997). Benthic detrital standing mass is generally low and variable, increasing through the more turbid downstream reaches (Shannon et al. 1996).

The Paria and Little Colorado Rivers, the primary sediment delivery systems downstream from Glen Canyon Dam, divide the Colorado River into three distinct turbidity zones that have a significant impact on mainstem aquatic food base communities (Stevens et al. 1997). The first 16 mi downstream from Glen Canyon Dam account for 60% of the total phytobenthic standing biomass throughout the remaining 242 mi of the river corridor (Blinn et al. 1995). Algae production decreases from Glen to Marble Canyon and is even lower in the Grand Canyon (Hall et al. 2010) because of the increasing suspended sediment loads that reduced light availability (Kennedy et al. 2013). *Cladophora* grows best in continuously submerged clear-water stable habitats, whereas *Oscillatoria* forms dense mat-like matrices of filaments and sand in the varial zone and other habitats with high suspended sediments that are more typical of many southwestern streams (Shaver et al. 1997).

Oscillatoria tends to colonize relatively early in disturbed or newly inundated zones, while colonization by *Cladophora* is reduced or occurs more slowly (McKinney et al. 1997). As *Oscillatoria* supports ten-fold fewer invertebrates than *Cladophora*, the input of terrestrially derived carbon has become vital to support the aquatic food base organisms. However, the leaves of the common nonnative *Tamarix ramosissima* along the river are an inferior food source for macroinvertebrates due to their high tannin content and slower decomposition rate compared to leaves of native cottonwoods and willows (Bailey et al. 2001).

Zooplankton is an important food resource for larval and juvenile native fish in the Colorado River system. The zooplankton found in regulated rivers is composed of both plankton derived from the reservoir (lentic species) and those derived from the streambed, backwaters, and tributaries of the river (lotic species) (Haury 1986). Lotic zooplankton and detritus are positively correlated with distance downriver from Glen Canyon Dam, increased discharge, and near-shore versus mid-channel locations. Lentic zooplankton abundance also increases at higher discharges and in near-shore habitats but are negatively correlated with distance downriver. It is possible that lentic zooplankton cannot survive and reproduce under the cold temperatures in the mainstem, although near-shore habitats provide a more stable environment than the mainstem, which may enhance rearing and development of lentic zooplankton (Benenati et al. 2001). Copepods are the most abundant zooplankton species in the Colorado River (AZGFD 1996). The biomass, productivity, and abundance of zooplankton (cladocerans, copepods, and ostracods originating primarily from Lake Powell) are highest in the Glen Canyon reach and drop sharply downstream (Tables F-2 through F-4).

There is evidence that Lake Powell zooplankton can survive downstream passage to Diamond Creek with only a small mortality rate due to abrasion. Thus, the zooplankton derived from Lake Powell has the potential of contributing to the aquatic food base throughout the river system to Lake Mead (Haury 1986). However, the Colorado River between Lake Powell and Lake Mead has a highly constricted channel and for the most part lacks backwaters of any significant area, which may account for the limited importance of zooplankton drift in the river (Blinn et al. 1995). Zooplankton may also have an affinity for *Cladophora* and other algae in the Glen Canyon reach, and are consumed by macroinvertebrates and fish in that reach (Benenati et al. 2001). These factors may also account for the diminished importance of zooplankton in the Marble and Grand Canyon reaches.

Generally, the responses of macroinvertebrates downstream of dams depend largely on the depth of the reservoir, the depth from which water is drawn, and on the ratio of low to high discharges (Jones 2013). Information on macroinvertebrates collected before and after closure of the Flaming Gorge Dam on the Green River in northeastern Utah is applicable to events that may have occurred in the Colorado River below Glen Canyon Dam (Blinn and Cole 1991; Pearson et al. 1968). Following closure of the Flaming Gorge Dam, macroinvertebrate genera declined from >70 to <30, while the mean macroinvertebrate abundance increased from 1,000 to 10,000/m^2 (Vinson 2001). Mayflies declined from 30 species to a single common species and two rare species. Midges and blackflies were the only other common post-dam insect taxa (Vinson 2001). Colonization of tailwaters by insects can be somewhat limited by lack of drift and small downstream insect population sizes that may limit recruitment from upstream flying adults (Vinson 2001).

River regulation by Glen Canyon Dam decreases turbidity in the tailwaters and permits increased algae growth on bottom substrates (Angradi 1994; Shannon et al. 1994), leading to an increased expansion of macroinvertebrate populations in the tailwater reach of Glen Canyon Dam (Blinn et al. 1992; Stevens et al. 1997). Algae biomass and production decrease downstream as water clarity decreases (Carothers and Brown 1991; Stevens et al. 1997; Hall et al. 2010). As is evident in Table F-1, this drives a downstream decrease in aquatic invertebrate biomass (e.g., *Gammarus*, midges, snails, and aquatic worms) (Carothers and Brown 1991; Stevens et al. 1997; Kennedy and Gloss 2005; Rosi-Marshall et al. 2010).

Various studies in the 1990s demonstrated that over 80% of the invertebrate biomass below Glen Canyon Dam was composed of *Gammarus*, midges, aquatic worms, and snails, many of which graze on epiphytes and other fine particulate matter (Blinn et al. 1998). Predation on insect eggs (e.g., by *Gammarus*) may contribute to the absence of mayflies and stoneflies below dams (Vinson 2001). In Glen Canyon, blackflies and midges support more than half of rainbow trout (*Oncorhynchus mykiss*) production but represent under 10% of total invertebrate production and abundance (Tables F-3 and F-4) (Kennedy et al. 2013). Midges and blackflies dominate invertebrate production in Marble and Grand Canyons (Table F-2); cobble bars are "hotspots" for midge and blackfly production (e.g., 2 to 10 times higher than other habitat types) (Kennedy et al. 2013). New Zealand mudsnails (*Potamopyrgus antipodarum*), *Gammarus*, aquatic worms, and midges dominate the current composition of the benthic community at Lees Ferry (Table F-3). In cobble substrates, New Zealand mudsnails and aquatic worms dominate the benthic biomass. They also dominate depositional habitats, although these areas tend to support lower benthic biomass (Cross et al. 2013). *Gammarus* dominates talus slopes and cliff faces, but these habitats generally have the lowest benthic biomass in the Lees Ferry reach. Blackflies (*Simulium arcticum*) are present in the Lees Ferry reach, but their biomass and abundance are generally low (Tables F-2 and F-4).

The absence of leaf litter and woody debris is probably largely responsible for the decreased biodiversity and density of invertebrates the Colorado River downstream from the Paria River (Purdy 2005). Clear and cool stenothermic releases and highly variable discharges from the dam and seasonal turbidity from tributary inputs also adversely impact macroinvertebrates (Shannon et al. 2001). The decrease in stream clarity lowers primary production and favors the growth of the less nutritious *Oscillatoria* in the lower reaches of the

TABLE F-1 Average Mean Habitat-Weighted Invertebrate Biomass at Select Sites in the Colorado River, July 2006–June 2009

	Habitat-Weighted Biomass (mg AFDM/m^2)[a]					
Taxon	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Acari (water mite)	<1	1	<1	<1	1	<1
Blephariceridae (net-winged midge)	0	0	0	2	<1	0
Ceratopogonidae (biting midge)	<1	<1	0	<1	<1	<1
Chironomidae (midge or chironomid)	163	113	58	30	43	45
Cladocera (water flea)	5	<1	<1	0	<1	0
Collembola (springtail)	0	<1	0	0	<1	0
Copepoda (copepod)	4	<1	<1	<1	<1	<1
Corixidae (water boatman)	0	0	0	<1	<1	0
Elmidae (riffle beetle)	0	<1	<1	6	3	3
Empididae (dagger or balloon fly)	0	<1	2	<1	1	<1
Ephemeroptera (mayfly)	0	0	0	0	<1	0
Gammarus (scud)	1,053	30	5	2	3	5
Hydropsychidae (net-spinning caddisfly)	0	0	2	3	2	<1
Hydroptilidae (microcaddisfly)	0	16	30	0	8	9
Molophilus (crane fly)	0	0	0	<1	<1	0
Nematoda (roundworm)	15	13	2	<1	<1	<1
New Zealand mudsnail	3,170	45	3	35	8	7
Oligochaetes (earthworm/bloodworm)	2,077	218	65	28	42	25
Ostracoda (seed shrimp)	25	<1	0	<1	<1	0
Physidae (bladder snail)	122	<1	0	1	<1	<1
Planariidae (planarian or flatworm)	114	9	<1	<1	<1	<1
Pyralidae (snout moth)	0	<1	0	<1	<1	3
Rhyacophilidae (free-living caddisfly)	0	42	0	0	<1	0
Simuliidae (blackfly)	100	858	35	50	49	44
Sphaeriidae (pea or fingernail clam)	14	<1	0	0	0	0
Zygoptera (damselfly)	0	0	0	0	<1	0
Total	6,862	1,345	202	155	160	141

[a] AFDM = ash-free dry mass. Site 1 is 16 mi downstream of Glen Canyon Dam (GCD, upstream of Paria River confluence), Site 2 is 45 mi downstream of GCD (downstream of Little Colorado River confluence), Site 3 is 78 mi downstream of GCD, Site 4 is 142 mi downstream of GCD, Site 5 is 180 mi downstream of GCD, and Site 6 is 240 mi downstream of GCD (upstream of Diamond Creek confluence).

[b] Biomass values <0.1 mg AFDM/m^2 for a taxon not included in total productivity value.

Source: Cross et al. (2011, 2013).

TABLE F-2 Average Mean Habitat-Weighted Invertebrate Production at Select Sites in the Colorado River, July 2006–June 2009

	Habitat-Weighted Productivity (mg AFDM/m^2/yr)[a]					
Taxon	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Acari (water mite)	0.3	5.0	4.9	3.7	7.0	4.5
Blephariceridae (net-winged midge)	0.0	0.0	0.0	12.4	1.6	0.0
Ceratopogonidae (biting midge)	0.3	4.1	1.4	0.2	1.1	3.6
Chironomidae (midge or chironomid)	717.6	1,103.2	549.0	437.8	634.6	575.7
Cladocera (water flea)	45.2	0.3	<0.1	0.0	<0.1	0.0
Collembola (springtail)	0.0	<0. 1	0.0	0.0	<0.1	0.0
Copepoda (copepod)	33.8	2.2	0.7	<0.1	1.6	0.5
Corixidae (water boatman)	0.0	0.0	0.0	<0.1	<0.1	0.0
Elmidae (riffle beetle)	0.0	2.3	2.6	24.9	17.7	18.3
Empididae (dagger or balloon fly)	0.0	7.3	11.7	4.4	12.2	6.7
Ephemeroptera (mayfly)	0.0	0.0	0.0	0.0	0. 7	0.0
Gammarus (scud)	6,113.8	129.1	18.1	13.5	36.7	68.9
Hydropsychidae (net-spinning caddisfly)	0.0	0.0	15.3	0.0	11.5	0. 7
Hydroptilidae (microcaddisfly)	0.0	134.0	159.2	17.9	41.9	58.6
Molophilus (crane fly)	0.0	0.0	0.0	0. 5	2.2	0.0
Nematoda (roundworm)	152.6	133.5	24.9	6.6	11.6	8.1
New Zealand mudsnail	8,637.0	74.4	8.3	27.8	32.1	27.5
Oligochaetes (earthworm/ bloodworm)	6,019.5	753.3	249.3	86.0	158.6	121.6
Ostracoda (seed shrimp)	124.9	0.3	0.0	<0.1	<0.1	0.0
Physidae (bladder snail)	690.2	4.0	0.0	8.2	0.6	4.6
Planariidae (planarian or flatworm)	571.2	45.9	1.2	0.1	4.2	0.8
Pyralidae (snout moth)	0.0	11.0	0.0	<0.1	0.5	19.0
Rhyacophilidae (free-living caddisfly)	0.0	316.4	0.0	0.0	3.8	0.0
Simuliidae (blackfly)	539.4	5,240.8	266.3	367.2	540.2	488.0
Sphaeriidae (pea or fingernail clam)	69.0	<0.1	0.0	0.0	0.0	0.0
Zygoptera (damselfly)	0.0	0.0	0.0	<0.1	0.0	0.0
Total[b]	23,714.8	7,967.1	1,312.9	1,011.2	1,520.4	1,407.1

[a] AFDM = ash-free dry mass. Site 1 is 16 mi downstream of Glen Canyon Dam (GCD, upstream of Paria River confluence), Site 2 is 45 mi downstream of GCD (downstream of Little Colorado River confluence), Site 3 is 78 mi downstream of GCD, Site 4 is 142 mi downstream of GCD, Site 5 is 180 mi downstream of GCD, and Site 6 is 240 mi downstream of GCD (upstream of Diamond Creek confluence).

[b] Productivity values <0.1 mg AFDM/m^2/yr for a taxon not included in total productivity value.

Source: Cross et al. (2011, 2013).

TABLE F-3 Average Mean Habitat-Weighted Invertebrate Abundance at Select Sites in the Colorado River, July 2006–June 2009

	Habitat-Weighted Abundance (number/m^2)[a]					
Taxon	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Acari (water mite)	20	455	423	324	562	318
Blephariceridae (net-winged midge)	0	0	0	<1	<1	0
Ceratopogonidae (biting midge)	2	52	11	1	25	31
Chironomidae (midge or chironomid)	6,814	9,814	4,602	2,929	3,716	3,172
Cladocera (water flea)	2,497	13	2	0	3	0
Collembola (springtail)	0	<1	0	0	<1	0
Copepoda (copepod)	4,973	404	118	2	174	62
Corixidae (water boatman)	0	0	0	<1	<1	0
Elmidae (riffle beetle)	0	48	38	41	41	19
Empididae (dagger or balloon fly)	0	5	21	11	25	5
Ephemeroptera (mayfly)	0	0	0	0	1	0
Gammarus (scud)	2,930	50	11	8	20	33
Hydropsychidae (net-spinning caddisfly)	0	0	5	0	1	<1
Hydroptilidae (microcaddisfly)	0	42	81	17	22	20
Molophilus (crane fly)	0	0	0	<1	<1	0
Nematoda (roundworm)	1,199	1,846	276	67	113	62
New Zealand mudsnail	74,033	382	110	229	187	120
Oligochaetes (earthworm/bloodworm)	32,988	7,270	2,774	533	1,117	922
Ostracoda (seed shrimp)	1,023	4	0	<1	3	0
Physidae (bladder snail)	279	<1	0	4	4	2
Planariidae (planarian or flatworm)	987	81	5	<1	21	2
Pyralidae (snout moth)	0	<1	0	<1	1	5
Rhyacophilidae (free-living caddisfly)	0	15	0	0	3	0
Simuliidae (blackfly)	419	3,180	316	327	476	352
Sphaeriidae (pea or fingernail clam)	122	<1	0	0	0	0
Zygoptera (damselfly)	0	0	0	0	<1	0
Total[b]	128,286	23,661	8,793	4,493	6,515	5,125

[a] AFDM = ash-free dry mass. Site 1 is 16 mi downstream of Glen Canyon Dam (GCD, upstream of Paria River confluence), Site 2 is 45 mi downstream of GCD (downstream of Little Colorado River confluence), Site 3 is 78 mi downstream of GCD, Site 4 is 142 mi downstream of GCD, Site 5 is 180 mi downstream of GCD, and Site 6 is 240 mi downstream of GCD (upstream of Diamond Creek confluence).

[b] Abundance values <0.1/m^2 for a taxon not included in total productivity value.

Source: Cross et al. (2011, 2013).

TABLE F-4 Distribution, Ecological Importance, and Favorable Temperature Range for Select Primary Producers

Taxa	Distribution	Ecological Importance	Favorable Temperature Range
Upright epiphytic diatoms	Throughout the river, but most abundant in the Glen Canyon Dam–Paria River reach	High, easily consumed by grazers	10–15°C (50–59°F)
Adnate epiphytic diatoms	Throughout the river, but most abundant in the Glen Canyon Dam–Paria River reach	Medium, not as easily consumed by grazers	15–20°C (59–68°F)
Cladophora glomerata	Throughout the river, but most abundant in the Glen Canyon reach	High, substrate for epiphytic diatoms	13–17°C (55–63°F)
Oscillatoria spp.	Throughout the river, but most abundant below Little Colorado River	Low, not generally consumed directly, poor substrate for diatoms	18–21°C (64–70°F)
Egeria densa	Glen Canyon reach	Medium-high, substrate for epiphytic diatoms, cover for fish	15–21°C (59–70°F)
Potamogeton spp.	Throughout the river, but most abundant in the Glen Canyon reach	Medium-high, substrate for epiphytic diatoms, cover for fish	20–22°C (68–72°F)
Fontinalis spp.	Glen Canyon reach	Medium-high, secondary substrate for epiphytic diatoms	10–15°C (50–59°F)
Chara spp.	Throughout the river, but most abundant in the Glen Canyon reach	Medium-high, substrate for epiphytic diatoms, cover for fish	18–25°C (64–77°F)

Source: Valdez and Speas (2007) and references cited therein.

Colorado River (Blinn et al. 1999). Macroinvertebrates are not generally associated with *Oscillatoria* because it is very compact, has little surface area for colonization, and largely lacks epiphytic diatoms (Blinn et al. 1995). For example, *Gammarus*, a major food source for trout and other fishes, prefers *Cladophora* due to its epiphytic diatoms. This relationship is strong from Glen Canyon Dam to Lees Ferry and weak from Lees Ferry to Diamond Creek (Patten 1998). This relationship does not exist between *Gammarus* and *Oscillatoria*. If *Cladophora* declines, then the contribution of *Gammarus* to the aquatic food base also declines, except perhaps in the drift (Patten 1998).

Drifting macroinvertebrates provide an important food resource for rainbow trout and other native and nonnative fish species. Flow regime, discharge, and distance from the dam influence drift of macroinvertebrates in the Colorado River (Shannon et al. 1996; Stevens et al. 1998; Sublette et al. 1998; McKinney et al. 1999). In general, a positive correlation exists between stream drift and discharge; however, reduced flows can increase stream drift through behavioral factors such as crowding, reduced oxygen concentrations, and avoidance of desiccation (Blinn et al. 1995). Kennedy et al. (2014) concluded that benthic density is the primary control on drift concentrations over long timescales (e.g., weeks to months), because increased benthic production will also increase drift. In contrast, changes in flow such as those occurring from hydropeaking have an important control on drift concentrations, but primarily on a shorter timescale (e.g., days) (Kennedy et al. 2014).

Tributary and terrestrial insects comprise a small portion of the stream drift in the Colorado River (Shannon et al. 1996), even though Minckley (1991) reported that terrestrial insects commonly occur in stomachs of humpback chub (*Gila cypha*). It is possible that terrestrial invertebrate drift increases during and immediately after rainstorms and is therefore an uncommon but locally important resource for river fishes through Grand Canyon (Shannon et al. 1996). Terrestrial and tributary insects contribute <0.001 and <0.1% of the total invertebrate biomass in the mainstem drift, respectively (Blinn et al. 1995). Fish production throughout Glen and Grand Canyon appears to be limited by the availability of midges and blackflies, and fish may exert top-down control over them (Carlisle et al. 2012). While blackflies and midges support between 43 and 50% of trout production, they only comprise a small percentage of total invertebrate secondary production and abundance in the Glen Canyon reach (Tables F-3 and F-4) (Cross et al. 2011).

Generally, physical, chemical, and biological attributes in the lower reaches of the Colorado River peak at or immediately downstream of tributaries. The connection between tributaries and the mainstem is important for the flow of nutrients, sediment, and wood that contribute to habitat heterogeneity and biodiversity in the mainstem (Kiffney et al. 2006). However, tributary sediment inputs can limit light availability and reduce algal production, thereby reducing food for aquatic invertebrates. High sediment loads may also limit the ability of fish to see their prey (Coggins and Yard 2011).

The Colorado River between Glen Canyon Dam and Lake Mead contains more than 400 ephemeral and 40 perennial tributaries; however, as many of the Colorado River tributaries are dry except during heavy summer rains, they contribute little to the mainstem aquatic food base (Haury 1986). All of the tributary streams have a natural seasonal range of temperatures and discharges unaffected by Glen Canyon Dam (NPS 2005). Oberlin et al. (1999) indicated that primary productivity and detritus, the major food resource for macroinvertebrates, are higher overall in clear-water tributaries and highest in those originating inside the Grand Canyon. Phytoplankton species richness also increases in clear-water tributaries (Crayton and Sommerfield 1979; Oberlin et al. 1999), increasing primary productivity and food quality in those environments (Henery 2005).

Common macroinvertebrates in the tributary streams include caddisflies, mayflies, stoneflies, midges, and blackflies. Drift of tributary macroinvertebrates into the mainstem contributes, at least locally, to the aquatic food base in the Colorado River. Macroinvertebrate productivity and diversity in the tributaries are lowest in the spring and summer, as flash floods in these seasons disrupt the benthic invertebrate communities (Oberlin et al. 1999). Tributaries provide ≤25% of the total organic stream drift in the Colorado River through Grand Canyon National Park (Blinn et al. 1995).

Tributary streams with travertine deposits (e.g., Havasu Creek) or dominated by bedrock (e.g., Matkatamiba Creek) have little inhabitable substrates for macroinvertebrates. Steep channel gradients and erosional habitat also limit benthos in some tributaries (Lawson 2007).

Overall, standing biomass of the Little Colorado River macroinvertebrate community was an order of magnitude lower (0.056 g/m^2 ash-free dry mass [AFDM]) than at the confluence with the Colorado River (0.25 g/m^2 AFDM). A high discharge with increased suspended sediment loads negatively affects macroinvertebrate biomass (Haden et al. 1999). Even extended periods of base flow (which tends to increase macroinvertebrates and algae) do not increase productivity for the areas of the Little Colorado River that contain most of the river's humpback chub population (Haden et al. 1999).

Some of the tributaries also contain New Zealand mudsnails, probably spread by recreationists (NPS 2005). Shannon et al. (2003a) reported the New Zealand mudsnail in cobble bars of 5 of 18 tributaries they sampled, but the snail did not extend more than 32 m upstream in those streams. Since New Zealand mudsnails prefer habitats with constant temperatures and flows and high primary productivity, flash floods may diminish their long-term establishment in tributaries (Shannon et al. 2003a). The risk of quagga mussel (*Dreissena rostriformis bugensis*) introduction to tributaries also appears low. Reservoirs on the upper reaches of the Little Colorado River may eventually support the quagga mussel. Establishment of the quagga mussel in many of the tributaries is unlikely due to high summer water temperatures above the mussel's upper lethal limit (Kennedy 2007).

F.2.1.3 Influence of New Zealand Mudsnail on the Aquatic Food Base

In addition to changes brought about by Glen Canyon Dam, the loss of native species and the addition of numerous nonnative species modified the aquatic ecosystem of the Colorado River within Grand Canyon (Johnson and Carothers 1987). This applies to the aquatic food base and fish species. Nonnative species, including those intentionally introduced, are often better competitors in the homogeneous habitats of regulated rivers (Stanford et al. 1996). To date, nonnative periphyton and rooted aquatic macrophytes have not caused adverse impacts to the aquatic food base in the Colorado River below Glen Canyon Dam. Section 4.17.3.4 discusses potential impacts that could occur if the diatom *Didymosphenia geminata* ("didymo") becomes established in the Colorado River.

The New Zealand mudsnail can tolerate a wide range of water temperatures (except freezing), salinity, and turbidity. It can also withstand short periods of desiccation. Densities of New Zealand mudsnail are usually highest in systems with high primary productivity, constant temperatures, and constant flow. It occurs in all types of aquatic habitats from eutrophic mud bottom ponds to clear rocky streams (USGS 2002; Sorensen 2010). Fitness of the New Zealand mudsnail peaks at 18°C (64°F), declining at cooler and warmer temperatures (NZMMCPWG 2007).

Numerous adaptations of the New Zealand mudsnail aid its spread within watersheds. For instance, adults can pass live through the digestive systems of some fish species, adults can float on masses of algae, and juveniles can float freely on the water surface (Kerans et al. 2005; NZMMCPWG 2007). While the New Zealand mudsnail is not common in streams prone to periods of sediment-moving flood flows, its tough shell, small size, and hydrodynamic shape make it likely to survive scouring flows (Holomuzuki and Biggs 1998; NZMMCPWG 2007).

Most New Zealand mudsnails in North America are asexually reproducing females that are born with developing embryos already present in their reproductive system (Sorensen 2010). Clonal reproduction increases the probability of success of introduction as only a single female can establish a new population (NZMMCPWG 2007). One female can carry up to 20 embryos and under proper conditions may account for over one million snails within one year (Shannon et al. 2003a).

Vinson et al. (2007) suggest that the New Zealand mudsnail introduction into the Green River below Flaming Gorge Dam may have led to a decline of total invertebrate abundance by over 25%. They concluded that decreases in mayflies due to competition from New Zealand mudsnails may jeopardize mayfly recolonization of the Green River following implementation of a more natural springtime flood flow regime. Where the New Zealand mudsnail dominates invertebrate production, it could become the dominant forage base for fishes that prey on macroinvertebrates (Vinson and Baker 2008). Field survey data in the Green River below Flaming Gorge Dam showed a sharp annual increase in the number of brown trout (*Salmo trutta*) and rainbow trout that consumed New Zealand mudsnail between 2001 and 2005 (Vinson and Baker 2008). Bioenergetic simulations suggest that fish diets high in New Zealand mudsnail would not meet energy requirements of fish, resulting in reduced growth and weight loss (Vinson et al. 2007; Vinson and Baker 2008) as discussed previously. For example, when the New Zealand mudsnail comprised between 71 and 81% of brown trout diet, the trout did not gain weight, and when the diet consisted of more than 81% New Zealand mudsnails, brown trout lost weight. Rainbow trout fed a diet of 42% New Zealand mudsnail began losing weight over the course of the experimental study (Harju 2007).

The presence of the New Zealand mudsnail is altering (e.g., causing a decline in) the entire food web in the Grand Canyon (Purdy 2005). The New Zealand mudsnail represents a trophic dead end in Glen Canyon because it has a high production and consumption of primary producers, but it does not support a substantial amount of production for higher trophic organisms. Minnows and suckers that possess pharyngeal teeth may be capable of consuming and crushing the shells of New Zealand mudsnails (NZMMCPWG 2007). However, the New Zealand mudsnail offers little or no energy compared to other common food items in those fish successful in crushing its shell (Ryan 1982).

F.2.2 Impacts of LTEMP Alternatives on the Aquatic Food Base

The Desired Future Conditions (DFCs) for the Colorado River Ecosystem Domain (Appendix A of the DEIS) include these two DFCs for the aquatic food base goals:

- The aquatic food base will sustainably support viable populations of desired species at all trophic levels.

- Assure that an adequate, diverse, productive aquatic food base exists for fish and other aquatic and terrestrial species that depend on those food resources.

Attaining these DFCs while meeting existing water delivery requirements is complex. Biological resources in regulated rivers are subject to a number of spatial and temporal changes in conditions downstream from a dam: reductions in seasonal flow variability, alterations in the timing of extreme flow events, pulses in flow during periods of peak power demands, reduced turbidity and increased water clarity, diel and seasonal constancy of water temperatures, armoring of substrates in the tailwaters, modified nutrient regimes, and the appearance of lentic plankton below the reservoir (Blinn and Cole 1991; Blinn et al. 1995; McKinney and Persons 1999). Flow and temperature are the two major factors that influence the condition and availability of the aquatic food base in the Colorado River between Glen Canyon Dam and Lake Mead. The following discussion supplements the analyses presented in Sections 4.5.2.1 and 4.5.3 of the DEIS.

F.2.2.1 Flow Effects on the Aquatic Food Base

Hydropeaking is the mode of hydroelectric generation that most alters the quantity and quality of habitats available to aquatic organisms. Effects can be direct (e.g., stranding, mortality, and habitat loss) or indirect (e.g., downstream displacement, depleted food production, increased stress) (Clarke et al. 2008). Impacts of flow fluctuations are typically greatest within the tailwaters of a dam and decline with distance downstream due to flow attenuation and the increasing influence of tributaries (Clarke et al. 2008; Patterson and Smokorowski 2011). Flow attenuation occurs downstream of Glen Canyon Dam, however, because of the constrained nature of the channel through most of Marble Canyon and the Grand Canyon, flow fluctuations from dam releases are still apparent in the lower Grand Canyon near Lake Mead (see Section 3.2.1.2 of the DEIS). The following provides discussion of flow effects on the aquatic food base with respect to the elements of base operations, adjustments of base operations, and trout management actions for the LTEMP alternatives.

Effects of Base Operations

Potential alternative-specific effects of base operations (i.e., operations in those years when no condition-dependent or experimental actions are triggered) on the aquatic food base depend on the differences in the monthly pattern in release volumes, minimum and maximum flows, daily flow ranges, and ramp rates. Monthly increases in release volumes may increase the permanently wetted zone, which could increase benthic production, if the increased monthly flows last long enough for benthic development to occur (e.g., weeks to months). Months of higher release volumes would also improve hydraulic connectivity with and maintenance of backwater habitats. Backwaters with more permanency potentially support increased planktonic and benthic communities. A decrease in the permanently wetted zone would occur when decreases in monthly release volumes occur (Reclamation 1995; Hoffnagle 2001; Melis et al. 2006; Behn et al. 2010). Pools of water left after high spring or summer flow months potentially provide habitat for mosquitoes (Blinn et al. 1995). While mosquitoes may contribute to the aquatic and terrestrial food base, they pose a potential health concern to humans.

Daily minimum flow is an important determinant of benthic standing crop because of the strong negative effects of desiccation on algae and invertebrates (Melis et al. 2006). Periods of low steady summer/fall releases (e.g., 5,000 to 8,000 cfs) are expected to result in warmer and more stable nearshore and backwater habitats and longitudinal river warming; while similar flows in winter are likely to produce greater overwinter algal and macroinvertebrate production (Blinn et al. 1995; Valdez et al. 2000). Wet channel area in low-angle habitats within the Glen Canyon reach is reduced by about 10% at 5,000 cfs compared to 8,000 cfs. This area reduction consists of about 16 ha; however, the effects on the aquatic food base from this habitat reduction may not be detectable (Melis et al. 2014).

Restricted minimum and maximum flows and reduced ramping rates of the Modified Low Fluctuating Flow regime adopted in the Glen Canyon Dam Record of Decision (Reclamation 1996) were intended to stabilize the area available for colonization by benthic algae, thereby decreasing losses through desiccation or freezing while increasing primary and secondary production (Blinn et al. 1995). Midges, blackflies, and *Gammarus* were not observed in the varial zone above the 10,600-cfs stage (Blinn et al. 1995).

The interactions between cycles of inundation and dewatering in varial zones play a major role in structuring algal communities in regulated desert rivers (Blinn et al. 1998). Periodic exposure of nearshore and backwater habitats can result in loss of invertebrates and primary producers through desiccation, while inundation can impact the aquatic food base through sediment deposition (Valdez et al. 1998). Atmospheric exposure of benthos can be more severe than flooding because organisms are directly killed rather than displaced or buried (Blinn et al. 1995). Fluctuating flows (>10,000 cfs/day) can fragment *Cladophora* from its basal attachment and increase its occurrence in the drift. Consuming drifting *Cladophora* (with its attached epiphytes and any invertebrates) allows rainbow trout to expend less energy in searching for food (Leibfried and Blinn 1987). Daily range in flows >10,000 cfs only occur during December and January (12,000 cfs) for Alternative B.

A stabilized discharge regime could increase algae production downstream of Glen Canyon Dam. In turn, this may have positive effects on invertebrate and fish production (Kennedy et al. 2013). Basal holdfasts of *Cladophora* can dry following periods of exposure as short as four hours in summer (Pinney 1991). Exposure to subzero winter air temperatures for only one night resulted in ≥50% loss of chlorophyll a and mass of *Cladophora* (Blinn et al. 1995). Recovery time may take several months (Blinn et al. 1992). Since algal communities provide the dominant food resource below dams, restricting the extent of the varial zone and maintaining wetted perimeter can be important to maintaining the overall food base (Blinn et al. 1998). Potential differences among alternatives based on daily range in flows are provided in Section 4.5.3 of the DEIS.

Warm or sub-freezing air temperatures could cause mortality of invertebrates stranded in the varial zone (Gislason 1985). The varial zone probably provides poor habitat for species with multiple life history stages (Jones 2013) by dewatering of emergence and oviposition sites (Vinson 2001). High rates of egg mortality due to exposure may partially explain the rarity of mayflies in the Colorado River. For example, adult female *Baetis* species land on rocks protruding from the water surface and then crawl underwater to lay their eggs on the underside of the rocks. These rocks may become dry for possibly 12 hours during the hydropeaking cycle, causing egg mortality (Kennedy 2013). The fact that midges and blackflies are broadcast spawners may explain why they are the predominant insects in the mainstem. Nevertheless, hydropeaking could still limit egg survival and thus recruitment for these species in the mainstem (Kennedy 2013). In the Glen Canyon Dam tailwaters, *Gammarus* standing stock and fecundity are lower, seasonal recruitment of young is briefer, and fewer young are recruited into the population in the varial zone compared to the permanently wetted zone. Also, *Gammarus* mortality increases in the varial zone (Angradi and Kubly 1993; Ayers and McKinney 1996; Ayers et al. 1998).

Invertebrates are continually moving and drifting to different positions in the river, thus stranding of a significant number of invertebrates in the varial zone would reduce the overall abundance in the river including that in the permanently wetted zone (Smokorowski 2010). However, there may be little colonization of shoreline areas during daily high flows, and as discharge decreases, large numbers of insects may not be present to enter the drift from areas being dewatered (Perry and Perry 1986). Nevertheless, reduction in the amplitude and duration of power peaking flow fluctuations may be an effective management strategy for enhancing aquatic insect biomass with the potential for increasing the survival and growth of fishes dependent on them (Gislason 1985).

Conversely, daily flow fluctuations may benefit the aquatic food base, if they have a strong negative impact on New Zealand mudsnails. In laboratory experiments, there was an average mudsnail survival of 50% from 1 to 7 hours of exposure, while 8 to 9 hours of exposure killed 88% of the mudsnails with none surviving a 14-hour exposure (Shannon et al. 2003b). However, New Zealand mudsnails occur on both stable and unstable habitats, so they can quickly colonize newly submerged habitats (Melis et al. 2006). Flow fluctuations may also increase the amount of organisms available to drift-feeding fish, although this may only occur for a short period (e.g., a few days or less) depending on the density and replacement capacity of benthic invertebrates. For example, a twofold daily variation in discharge resulted in a >10-fold increase in drift concentrations of *Gammarus* and New Zealand mudsnails while blackfly drift concentrations decreased by over 80% as discharge doubled. Midge drift concentrations increased proportional to discharge (Kennedy et al. 2014).

As the daily range in flows increases, there is greater divergence in habitat conditions between low and high flows, and there will likely be fewer taxa that can withstand such variability. Consequently, the ratio of the regulated high and low flows may become as important as the base flow as an influencing factor determining biotic composition (Jones 2013). Ramping rate restrictions may allow sufficient time for aquatic macroinvertebrates to respond to daily flow fluctuations (Patterson and Smokorowski 2011). Rapid up-ramping can result in rapid increases in shear stress, potentially causing catastrophic drift or the large scale displacement of invertebrates from the sediment (Gibbins et al. 2007). Perry and Perry (1986) observed a greater number of aquatic invertebrates stranded when the down ramping rate was rapid; indicating that unlimited down ramping is a potential cause of increased invertebrate mortality (Smokorowski 2010). Also, high ramping rates potentially favor adnate diatom species over the more upright species, the latter of which macroinvertebrates and fishes more readily consumed (Hardwick et al. 1992; Pinney 1991; Biggs 1996).

Miller and Judson (2014) observed that, during a daily hydropeaking schedule, macroinvertebrate drift biomass below Flaming Gorge Dam in the Green River increased during the rising limb of the daily hydrograph and declined prior to the cessation of the peak. Macroinvertebrate drift increases were correlated with the biomass of drifting vegetation. As the study by Miller and Judson (2014) occurred over winter, the rate of vegetation export declined over time due to senescence caused by decreased light levels and cooler temperatures. This at least partly accounted for the observed declines in macroinvertebrate drift after 30 to 60 days (Miller and Judson 2014).

During base operations, up-ramping rates are the same at 4,000 cfs for all alternatives except for Alternatives F and G that would not have a daily range in flows. Down-ramping rates would be highest for Alternative B (4,000 cfs for November through March and 3,000 cfs in the other months), followed by the Alternatives C, D, and E (2,500 cfs) and Alternative A (1,500 cfs). Alternatives F and G both feature steady flows in all months.

Experimental Treatments

High-Flow Experiments. Most experimental adjustments of base operations relate to high-flow experiments (HFEs). The existing HFE protocol calls for spring HFEs to occur in March–April and fall HFEs to occur in October–November with magnitudes ranging from 31,500 to 45,000 cfs (Reclamation 2011a). Most HFEs would last from less than one hour to 96 hours, although HFEs longer than 96 hours could occur under Alternatives C, D, and G. There is a potential for more than one HFE to occur within the same year or between years, with a potential for up to 40 HFEs during the LTEMP period (Alternatives C, F, and G). Food webs close to Glen Canyon Dam are more energy inefficient and are expected to exhibit lower resistance to experimental flood perturbations compared to food webs downstream of major tributaries (Cross et al. 2013).

HFEs conducted in the spring and fall represent contrasting conditions, particularly with regard to light, temperature, and invertebrate biomass. Plant and macroinvertebrate recovery times may be shorter for spring HFEs than for fall HFEs as a result of longer day lengths and warmer river temperatures in spring and summer. Spring HFEs can cause ponding of tributary flows that enter the Colorado River, creating temperature refuge areas within the mainstem (Valdez et al. 2000). Spring HFEs can also re-suspend organic material stored along the shoreline and redistribute it into the mainstem (Valdez et al. 2000). The majority of the aquatic food base taxa would recover within 1 to 4 months after a spring HFE as observed for the spring 1996 and 2008 HFEs (Blinn et al. 1999; Rosi-Marshall et al. 2010), although some taxa may recover more slowly (Cross et al. 2011). Shannon et al. (2001) reported high rates of invertebrate drift for two months after the spring 1996 HFE. A post-flood increase in production and drift of midges and blackflies is expected after a spring HFE (Cross et al. 2011) likely due to the flushing of fines in the interstitial spaces between gravel and around macroalgae holdfasts used by these invertebrates for cover. *Gammarus* is expected to be slower to recover because of its greater susceptibility to being exported by river currents than most invertebrate species (Reclamation 2011a). Also, slow-growing taxa such as *Gammarus* take longer to recover to pre-flood levels relative to faster growing taxa with aerial life stages such as blackflies and midges (Robinson and Uehlinger 2008).

Fall HFEs precede winter months of minimal insolation, low temperatures, and reduced gross primary productivity. Thus, recovery times for aquatic food base organisms take longer than for spring HFEs (Melis et al. 2006). Following the fall 2004 HFE, *Gammarus* was extremely scarce for many months in Lees Ferry (Melis et al. 2006). Even longer recovery times could occur if a fall HFE is followed by a spring HFE. The 4 to 5 months between a fall and spring HFE could preclude full recovery of most benthic invertebrate assemblages. The following spring HFE could scour the remaining primary producers and susceptible invertebrates and further delay recovery. A spring HFE followed by a fall HFE may not have as great an impact because of the rapid recovery of the food base expected over the summer (Reclamation 2011a).

The 2008 spring HFE reduced annual invertebrate production in the Lees Ferry tailwater by >50%, driven primarily by significant reductions in production of New Zealand mudsnails and *Gammarus*. Large numbers of *Gammarus* dislodged during high flows are transported considerable distances downstream, making them available to fishes. Windrows of stranded *Gammarus* carcasses along some shorelines following the spring 1996 controlled flood (Valdez 1999) became available to terrestrial consumers such as shorebirds, lizards, and spiders. Reductions in mudsnails and *Gammarus* persisted at least 15 months after the HFE (when the study concluded) and coincided with a significant decline in the annual production of these taxa (e.g., New Zealand mudsnail production declined from 11 to 13 g AFDM/m^2/yr to 2 g AFDM/m^2/yr and *Gammarus* production from 7 to 8 g AFDM/m^2/yr to 3 g AFDM/m^2/yr). Reductions in aquatic worms recovered in about 4 to 6 months (Rosi-Marshall et al. 2010). However, midges and blackflies increased by 30 and 200%, respectively, in the year following the HFE, and they supported a 200% increase in rainbow trout production (Cross et al. 2011). During the flood, the concentrations of invertebrate prey available in the drift increased from an average of 0.093 mg/m^3 AFDM before the flood to an average 0.163 mg/m^3 after the flood (Rosi-Marshall et al. 2010; Cross et al. 2011).

The concentrations of midges and blackflies in the drift increased 400 and 800%, respectively, after the 2008 HFE, and this effect persisted for at least 15 months. Biomass and production of both groups also increased after the HFE (Rosi-Marshall et al. 2010; Cross et al. 2011). The March 2008 HFE resulted in an increase in the area of backwater habitat that persisted for at least two months, but returned to conditions similar to those before the HFE by about 6 months after the HFE (Melis 2011). In addition to scouring benthic algae and invertebrates, high flows can capture large quantities of terrestrial organic matter that may temporarily increase the amount of food base available for drift-feeding fish (Valdez and Hoffnagle 1999; Gloss et al. 2005).

Generally, more frequent HFEs may cause a shift to more resistant taxa or to new taxa that would colonize the river. However, if such taxa are not present, more frequent HFEs may reduce macroinvertebrate diversity and possibly abundance, resulting in a reduction in the aquatic food base (Reclamation 2011a). Any benefits from HFEs along downstream segments of the Colorado River (particularly the lower portion of the Grand Canyon reach) will likely be smaller in magnitude than in the Lees Ferry reach (Melis 2011; Kennedy et al. 2013). The average number of HFEs during the LTEMP period would be 39.3 under Alternative F; range from 17.1 to 24.5 under Alternatives C, D, E, and G; and be only 7.2 under Alternative B and 5.5 under Alternative A.

The most notable differences among the alternatives is for Alternative A, which would not have HFEs after 2020; Alternative B, which would not exceed one spring or fall HFE every other year; and Alternative E, which would not have spring HFEs during the first 10 years (Table 2-2 of the DEIS).

A comprehensive study on the ecological effects of repeated HFEs in the River Spöl in Switzerland indicated that one or two high-flow events per year can enhance and sustain long-term ecological integrity (Scheurer and Molinari 2003) and that such releases must be repeated on a regular basis (annually) to maintain their benefits (Robinson and Uehlinger 2008). The first experimental flood in the River Spöl reduced macroinvertebrate abundance by about 50%. However, subsequent experimental floods had less effect, indicating that a new assemblage had established that was more resilient to flood disturbance. The response of macroinvertebrates to experimental floods occurs over a period of years, rather than months, as species composition adjusts to the new flow conditions (Robinson and Uehlinger 2008). Robinson et al. (2003) observed that the abundance of amphipods and planarians decreased while the abundance of baetid mayflies, blackflies and midges increased. Some mayfly, stonefly, and caddisfly taxa initially decreased in abundance but subsequently increased. The results of experimental floods in the River Spöl imply that the experimental flood regime needs maintaining to sustain the development of a more natural macroinvertebrate assemblage (Robinson et al. 2003). While three to five consecutive HFEs from Glen Canyon Dam may alter the aquatic food base composition, the absence of an HFE for one or more seasons might reset the current aquatic food base community (Reclamation 2011a). It is anticipated that, regardless of the HFE regimen, midges and blackflies would remain important components of the aquatic food base downstream of Glen Canyon Dam.

A large portion of the aquatic food base in the Lees Ferry reach would likely be scoured by an HFE of 41,000 to 45,000 cfs regardless of the time of year. The initial hydrostatic wave produces the scouring effect, and the duration of the flow is an important factor in transporting the material downstream (Rosi-Marshall et al. 2010). The HFE conducted in March 1996 (7-day discharge of 45,000 cfs) resulted in benthic scour and entrainment of both primary and secondary producers at all study sites along the 239-mi river corridor. Over 90% of the benthos was removed by the hydrostatic wave or within 24 hr from the start of the test flood. Also, drift mass reached highest levels during the first 2 days of the HFE (an order of magnitude higher than under normal dam operations) and subsided after that period (Shannon et al. 2001). Recovery rates to pre-flood levels were fast for benthic algae (1 month) and invertebrates (2 months) (Blinn et al. 1999). Recovery of the macrophytes *Chara*, *Potamogeton*, and *Elodea* to pre-flood conditions took 1 to 7 months (Shannon et al. 2001).

It is hypothesized that mucilaginous algae found in miscellaneous algae, macrophytes, and bryophytes (MAMB) can outcompete *Cladophora* under the combination of reduce nutrient conditions and elevated discharge regimes of about 25,000 cfs. However, if discharge increases to 45,000 cfs or more, MAMB will scour, allowing *Cladophora* to recolonize regardless of nutrient conditions because of strong holdfast attachment and lack of competition (Benenati et al. 2000). HFEs up to 45,000 cfs may occur under Alternatives C, D, and G.

HFEs longer than 96 hours may also occur under Alternatives C, D, and G. These longer-duration HFEs could scour much of the aquatic food base, especially within the Glen Canyon reach, and reduce the standing crop of benthic invertebrates. The extended-duration HFEs may increase the aquatic food base available for drift-feeding fishes, particularly during the initial hours of the flood. An extended-duration HFE may also help to control the abundance of New Zealand mudsnails in the Glen Canyon reach, but possibly contribute to their downstream abundance. Potential effects of sustained spring flows include:

- High, turbid main-channel flow and a surge of increased macroinvertebrate drift, increased feeding opportunities for non-sight feeders, and increased density of terrestrial invertebrates washed from shoreline.

- Rebuilt backwater habitats and increased primary and secondary production in backwaters following redistribution of organics (Valdez et al. 1998).

Steady Flows. Steady flows (or nearly steady flows with some instantaneous fluctuations associated with ancillary services) would occur prior to or following spring and/or fall HFEs (prior to spring and fall HFEs under Alternative C and before fall HFEs only for Alternatives D and E; Alternatives F and G already feature steady flows). Potential effects of steady flows include: (1) warmer shoreline and backwaters and an increase in backwater production; (2) warmer main channel and an increase in primary and secondary production and potential for parasite maturation and proliferation; and (3) stable main channel and less turbidity and an increase in shoreline primary and secondary production and reduced macroinvertebrate drift as food for fish (Valdez et al. 1998). However, mainstem warming, particularly in the Glen Canyon and Marble Canyon reaches, would be limited. Ralston et al. (2007) observed that biological and physical parameters were unaffected by daily fluctuations in flow of 2,700 cfs and steady-flow releases. Reduced flow fluctuations prior to an HFE could increase production of primary producers and consumers. The HFE could increase drift biomass. Reduced flow fluctuations following an HFE could hasten benthic recolonization.

Low Summer Flows. Low summer flows may be tested for two or three years under Alternatives C, D, and E; and are an annual component of Alternative F. The low summer flow tests would involve flows between 5,000 and 8,000 cfs to warm the Colorado River at the confluence with the Little Colorado River to at least 13°C (55°F). This would necessitate increasing mean daily flows in other months relative to base operations. Low summer flow tests may increase primary and secondary benthic production but reduce macroinvertebrate drift. In particular, the density of New Zealand mudsnails may increase under low summer flows. However, the opposite conditions, compared to base operations without low summer flow tests, may occur in non-summer months. Potential impacts on the aquatic food base from low summer flows under Alternative F are described in Section 4.5.3.6 of the DEIS.

Hydropower Improvement Flows. Hydropower improvement flows (increased fluctuation levels proposed as an experiment under Alternative B) would entail a daily change from a minimum flow of 5,000 cfs to a maximum flow of 15,000 to 25,000 cfs (depending on season). This could decrease primary and secondary production, although macroinvertebrate drift may increase. Down ramp rates of 5,000 cfs/hr may increase stranding of organisms in the varial zone compared to base operations that range from 1,500 cfs/hr (Alternatives A, F, and G) to 4,000 cfs/hr (Alternative B from November through March). Conversely, higher up-ramp rates of 5,000 cfs/hr coupled with sustained high flows may flush increased amounts of terrestrial invertebrates (and other items such as leaf litter) from shoreline areas into the drift compared to base operations for all alternatives (up-ramp rates of 4,000 cfs/hr).

Sustained Low Flows for Benthic Invertebrate Production. An aquatic resource-related experiment unique to Alternative D would be to test the effects of sustained low weekend flows in May through August on benthic invertebrate production and diversity. It has been hypothesized that the large varial zone created by fluctuating flows limits recruitment of mayflies (order Ephemeroptera), stoneflies (order Plecoptera), and caddisflies (order Trichoptera), collectively referred to as EPT, due to high egg mortality. If EPT deposit eggs principally along the shallower shoreline areas, then eggs laid during stable low flows over the weekend would not be subjected to drying prior to hatching. Depending on the findings from the first test, this experiment may be conducted two to three times during the LTEMP period, but not during the first 2 years. In addition to potentially increasing EPT, sustained low weekend flows may benefit other aquatic food base organisms that have terrestrial adult life stages such as dragonflies and true flies (including midges and blackflies). Some loss of benthic production is possible in the shoreline areas that remain dewatered over the weekend. If this results in an unacceptable risk (e.g., decreased benthic production), the experiment would not be repeated. There is also the strong possibility that this experimental procedure may result in confounding interactions with trout management flow (TMF) experiments, also expected to be conducted during the LTEMP period.

Trout Management Flows. The 2003 Ecological Restoration Flows that began on January 1, 2003, consisted of daily fluctuations between 5,000 and 20,000 cfs in an attempt to disadvantage nonnative fish, particularly trout, during their winter spawning period. Overall, the 2003 Ecological Restoration Flows caused a drop in benthic biomass at cobble bars in Glen Canyon during the January to March flows followed by recovery through the summer (Shannon et al. 2003b). The flows did not have a long-term adverse impact on New Zealand mudsnail biomass and densities throughout the river. For example, at –3 Mile Bar, mudsnail biomass dropped by 70% between December and January collections; however, by June, New Zealand mudsnails had recovered to 90% of the December estimate (Shannon et al. 2003b).

TMFs conducted in spring and summer months (May–July), featured in all alternatives but Alternative A, would consist of several days at relatively high sustained flows (e.g., 20,000 cfs) followed by a rapid drop to low flows (e.g., 5,000 cfs) which would be held for a brief period (e.g., <24 hr). This pattern would be repeated for a number of cycles. Conditions for primary production should decrease slightly with increased turbidity during the higher discharge portion of TMFs (Reclamation et al. 2002). Although a temporary increase in total wetted area would occur under TMFs, areas would not be inundated for sufficient time to allow for benthic colonization (Benenati et al. 1998; Blinn et al. 1995). Thus, desiccation losses due to substrate exposure from dewatering of the varial zone would be minimal. Aquatic food base drift may increase during up-ramping to 20,000 cfs/hr associated with TMFs. Drift biomass has been observed to increase during the rising limb of the hydrograph (Miller and Judson 2014).

F.2.2.2 Temperature Effects on the Aquatic Food Base

One of the primary effects of dams, particularly those with hypolimnetic releases, is the change in water temperatures, which is primarily responsible for the decline in invertebrate biodiversity. Warmer winter water temperatures can impact invertebrates in a number of ways including loss of physiological signals; disruption of normal growth, fecundity, and emergence; lack of winter chill to break insect egg or larval diapause; and early emergence. Cooler summer water temperatures can also impact invertebrates. For example, water temperatures high enough to complete development may not occur. Other impacts may include decreased fecundity, temporal separation of male and female emergence, delayed emergence, and prolonged emergence. The greater thermal constancy in annual and diel stream water temperatures downstream from dams also tends to decrease food base biodiversity (Vinson 2001).

Seasonal variation in water temperatures decreased gradually from Glen Canyon Dam closure in 1963 until about 1971, when water began to be drawn from the hypolimnion of Lake Powell. Main channel temperatures are now relatively isothermal at 7.2 to 10°C (45 to 50°F), but warm somewhat downstream in summer. There is an estimated maximum warming of the Colorado River mainstem of about 1°C (1.8°F) for every 35 mi, and water released at 10°C (50°F) from Glen Canyon Dam is expected to warm to about 17°C (62.6°F) near Diamond Creek (RM 225) in May or June (Benenati et al. 2002; Valdez 1994). Backwater habitats near the channel margins are one of the few aquatic habitats that warm above these levels. Backwater temperatures tend to warm with distance downstream from the dam (Valdez et al. 1998).

In winter, the mainstem water temperature near Diamond Creek is only about 1°C (1.8°F) higher than at Glen Canyon Dam (Cross et al. 2013). From 1988 to 2005, the average temperature of water released from Glen Canyon Dam was 9°C (48.2°F), and annual high temperatures at Diamond Creek between 1990 and 2002 were about 18°C (64.4°F). A drought that began in 2003 reduced water levels in Lake Powell and resulted in water temperatures that reached an annual high of 21°C (69.8°F) at Diamond Creek in 2005 (Hamill 2009).

In a two-week laboratory study, epiphytic diatom communities from the cold tailwaters of Glen Canyon Dam (12°C [54°F]) were incubated at 18 and 21°C. No change occurred in diatom composition between 18 and 21°C (64 and 70°F), but a significant change occurred between 12 and 18°C (54 and 64°F). At the higher water temperatures, smaller and closely adnate taxa became more important numerically than larger, upright diatoms (Blinn et al. 1989). This shift in diatom species composition may affect macroinvertebrates that feed on diatoms (Lechleitner 1992). Table F-4 provides the distribution, ecological importance, and favorable temperature range for select primary producers in the Colorado River, while Table F-5 provides temperature requirements for common zooplankton taxa.

TABLE F-5 Temperature Requirements for Common Zooplankton

	Temperature, °C (°F)		
Species	Minimum	Maximum	Optimum
Daphnia pulex (cladoceran)	10 (50)	28 (82)	20 (68)
Daphnia galeata (cladoceran)	10 (50)	25 (77)	20 (68)
Daphnia lumholtzi (cladoceran)	10 (50)	30 (86)	25 (77)
Leptodora sp. (cladoceran)	15 (59)	30 (86)	20 (68)
Bosmina sp. (cladoceran)	6 (43)	28 (82)	20 (68)
Diaphanosoma sp. (cladoceran)	10 (50)	30 (86)	25 (77)
Rotifers	15 (59)	30 (86)	25 (77)
Calanoid copepods	10 (50)	30 (86)	25 (77)
Cyclopoid copepods	10 (50)	30 (86)	25 (77)

Source: Valdez and Speas (2007).

If stream temperatures are raised by only a few degrees in winter, many aquatic insects that normally emerge in May or June may emerge in February or March and face death by freezing or will be prevented from mating because they are inactivated by low air temperatures. In addition, increases in stream temperatures may exaggerate the separation between the emergence of males and females (e.g., males may emerge and die before females emerge) (Nebeker 1971). Overall, temperatures above or below the optimum can lead to the production of small adults and lower fecundity (Vannote and Sweeney 1980). Slower warming of streams throughout the summer can reduce fecundity of emerging adults, exaggerate the separation of male and female emergence, prolong the emergence period of individual generations (which reduces the number of insects emerging at any given time, which may increase the individual risk of predation by trout or other fish), and reduce the growth rate such that emergence might occur later in the year when air temperatures are suboptimal for mating (Rader et al. 2008; Vinson 2001).

The lack of temperature variability in the Colorado River downstream of Glen Canyon Dam has selected for macroinvertebrates that do not require temperature cues to complete their development. This may at least partially account for the low levels of mayflies and caddisflies and the absence of stoneflies in the mainstem of the Colorado River (Oberlin et al. 1999). Fecundity of *Gammarus* in the tailwaters of Glen Canyon Dam is lower than that reported for it in other locations, probably due to water temperatures being well below the optimum of 18°C (64°F) for reproduction (Ayers et al. 1998). Table F-6 provides the distribution, importance to higher trophic levels, and temperature range for common benthic macroinvertebrates that occur in the Colorado River.

There is the possibility of an increase in the distribution and prevalence of fish diseases and parasites from river warming (Hoffnagle 2001; Valdez et al. 2000). Warmer, more stable backwaters could provide additional habitats for the Asian tapeworm (*Bothriocephalus acheilognathi)* and anchor worm (*Lernaea cyprinacea*) to substantially increase in abundance,

TABLE F-6 Distribution, Importance to Higher Trophic Levels, and Temperature Range for Common Benthic Macroinvertebrates Downstream of Glen Canyon Dam

Taxa	Distribution in Project Area	Importance to Higher Trophic Levels	Temperature Range in Project Area[a]	Favorable Temperature Range[a]
Gammarus lacustris (amphipod)	Glen Canyon Dam–Paria River (also important component of drift below this reach)	High	7–10 (45–50)	7–29 (45–84)
Simulium (blackfly)	RM 1.0 to Lake Mead and various tributaries	Medium-high	5–31 (41–88)	10–26 (50–79)
Cricotopus (midge)	Glen Canyon Dam–Paria River (also important component of drift below this reach)	Medium	7–10 (45–50)	15–21 (59–70)
Eukiefferiella (midge)	Glen Canyon Dam–Paria River (also important component of drift below this reach)	Medium	7–10 (45–50)	12–18 (54–64)
Orthocladius (midge)	Glen Canyon Dam–Paria River (also important component of drift below this reach)	Medium	7–10 (45–50)	8–18 (46–64)
Chironomus (midge)	River Mile 1.0 to Lake Mead	Medium	4–23 (39–73)	9–25 (48–77)
Aquatic worms	Glen Canyon Dam–Paria River (also important component of drift below this reach)	Low	4–23 (39–73)	8–25 (46–77)
Aquatic snails	Glen Canyon Dam–Paria River	Low	7–10 (45–50)	7–39 (45–102)
Potamopyrgus antipodarum (New Zealand mudsnail)	Glen Canyon Dam–Paria River	Low	4–23 (39–73)	7–28 (45–82)
Pisidium (pill clam)	Glen Canyon Dam–Paria River	Low	7–10 (45–50)	2–20 (36–68)
Dugesia (planarian)	Glen Canyon Dam–Paria River	Low	7–10 (45–50)	5–16 (41–61)
Baetis (mayfly)	Various tributaries	High	3–31 (37–88)	4–18 (39–86)
Hydropsyche (caddisfly)	Various tributaries	High	3–3 (37–88)	7–30 (45–86)
Megaloptera: Corydalidae (dobsonflies)	Various tributaries	High	5–28 (41–82)	5–30 (41–86)

[a] Temperature in °C (°F).

Source: Valdez and Speas (2007) and references cited therein.

resulting in their spread along the mainstem and into additional warmwater tributaries. Reported maximum temperature warming above those in the main channel for nearshore habitats range from 2.2°C (4.0°F) in eddies to 13°C (23.4°F) in backwaters (Vernieu and Anderson 2013). Warming of nearshore areas is somewhat ephemeral (e.g., decreases at night and during day under windy or cloudy conditions) (Vernieu and Anderson 2013). Temperatures greater than 20°C (68°F) would allow maturation of the Asian tapeworm, while temperatures greater than 15°C (59°F) would allow maturation of the anchor worm (Valdez et al. 1998). Section 4.5.2.4 of the DEIS discusses fish parasite and disease incidence for mainstem locations. Table F-7 presents temperature requirements of the Asian tapeworm, anchor worm, and trout nematode. Whirling disease infection prevalence and disease severity reaches its highest levels at 10–15°C (Steinbach Elwell et al. 2009).

As analyzed in Section 4.5.3 of the DEIS, temperature differences among alternatives would be minimal. Therefore, no significant changes in the aquatic food base due to elements of the base or condition-dependent operations are expected.

F.2.3 Conclusion

Table 4.5-1 of the DEIS summarizes the impacts from the alternatives on the aquatic food base, while Section 4.5.3 of the DEIS presents the impacts of each alternative in more detail. Under Alternative A, existing conditions and trends in the composition, abundance, and distribution of the aquatic food base are expected to persist over the LTEMP period. The cessation of HFEs after 2020 may result in a shift to a food base community not dominated by midges and blackflies (important contributors to the diet of trout). Water temperatures, and their resultant influences on species composition, diversity, and production of the aquatic food base, would be similar to current temperatures in the Colorado River downstream of Glen Canyon Dam.

TABLE F-7 Temperature Requirements for the Asian Tapeworm, Anchor Worm, and Trout Nematode

	Host Activity Temperature Requirements[a]			Infestation Temperature Requirements[a]		
Species	Minimum	Maximum	Optimum	Minimum	Maximum	Optimum
Asian tapeworm	18 (64)	20 (68)	19 (66)	20 (68)	30 (86)	25 (77)
Anchor worm	20 (68)	30 (86)	25 (77)	18 (64)	30 (86)	25 (77)
Trout nematode	16 (61)	20 (68)	18 (64)	16 (61)	20 (68)	18 (64)

[a] Temperature in °C (°F)

Source: Valdez and Speas (2007).

Under Alternative B, benthic food base production would be similar to Alternative A. HFEs conducted less often than annually may lower the potential to establish a food base adaptable to flood conditions (i.e., one dominated by midges and blackflies). Hydropower improvement flows could decrease benthic food base production, which over the long term may also decrease drift (Kennedy et al. 2014). Over the short term, TMFs could also cause short-term increases in drift rates and slightly decreased primary production compared to Alternative A. Temperature impacts on the aquatic food base under Alternative B would be similar to those under Alternative A.

Under Alternative C, benthic food base productivity may be higher in December through June compared to Alternative A due to higher volumes and larger wetted area, but lower from August through November compared to Alternative A due to lower volumes and smaller wetted area. The more frequent HFEs compared to Alternative A would favor midge and blackfly production. Low summer flows are expected to lower food base production compared to higher flow conditions. Over the short term, TMFs could increase drift rates and slightly decrease primary production compared to Alternative A. Slightly warmer water temperatures for August and September at RM 225 under Alternative C may slightly increase food base production compared to Alternative A, although this could be offset by changes in diatoms from stalked to adnate forms and favoring *Oscillatoria* over *Cladophora*.

The relatively consistent monthly release volumes under Alternative D compared to Alternative A would produce a more consistent and stable aquatic food base. The more frequent HFEs under Alternative D are expected to favor midge and blackfly production compared to Alternative A. Low summer flows are expected to lower food base production compared to higher flow conditions. Over the short term, TMFs could increase drift rates and slightly decrease primary production compared to Alternative A. Sustained low weekend flows in May through August under Alternative D would be tested to determine if they increase benthic food base production and diversity including the recruitment of mayflies, stoneflies, and caddisflies (important food base organisms currently rare to absent throughout much of the mainstem below Glen Canyon Dam). Temperature impacts on the aquatic food base under Alternative D would be similar to those under Alternative C.

Under Alternative E, relatively consistent monthly release volumes would favor aquatic food base productivity, but this effect would be offset by larger daily fluctuations. The frequent HFEs under Alternative E will favor midge and blackfly production, though the number of HFEs would be less than under Alternative C, D, F, and G. Temperature impacts on the aquatic food base for Alternative E would be similar to those under Alternative C and D.

Under Alternative F, food base biomass from July through the following March would be potentially less compared to all other alternatives due to comparatively lower flow volumes. Flow stabilization may allow for high benthic densities of New Zealand mudsnails. Over the long term, increased benthic production from flow stabilization may increase drift rates of food base organisms (Kennedy et al. 2014). Higher flow volumes in April through June may increase benthic food base biomass compared to Alternative A. The frequent HFEs will favor blackfly and midge production. The warmer water temperatures for August and September at RM 225 under Alternative F may slightly increase food base production even more than Alternative D, although this could similarly be offset by changes in diatoms from stalked to adnate forms and favoring *Oscillatoria* over *Cladophora*.

Under Alternative G, consistent and stable aquatic food base conditions would persist throughout the year. Benthic food base biomass would probably be greater under Alternative G compared to Alternative F, because flows from July through the following February would be higher. However, stable flows may favor dominance by the New Zealand mudsnail. Potentially higher drift rates from spring flows under Alternative F would not occur under Alternative G. However, increased benthic production may increase drift rates over the long term (Kennedy et al. 2014). The frequent HFEs are expected to favor blackfly and midge production. Temperature impacts on the aquatic food base for Alternative G would be similar to those under Alternative C, D, and E.

F.3 MODELING EFFECTS OF LTEMP ALTERNATIVES ON RAINBOW TROUT AND HUMPBACK CHUB

This section describes the methodology, results, and conclusions from a model developed in support of the LTEMP DEIS by Yackulic (Grand Canyon Monitoring and Research Center [GCMRC]), Coggins (U.S. Fish and Wildlife Service [FWS]), and Korman (EcoMetrics) to evaluate effects of alternatives on rainbow trout and humpback chub populations. Although other models were considered for use, the combined rainbow trout-humpback chub model described here was developed to incorporate recent information from the Natal Origins, Juvenile Humpback Chub Monitoring, and Near-Shore Ecology projects being conducted by GCMRC and to utilize newer approaches to modeling humpback chub population demographics. Additionally, there was a need to develop the model in a software environment in which batch processing of model runs for multiple hydrologic and sediment input scenarios for each alternative would be feasible and computationally efficient. The model used existing data to inform parameter estimates whenever possible.

F.3.1 Model Overview

The trout-chub model consists of three combined submodels: (1) a model of rainbow trout population dynamics in the Lees Ferry reach, (2) a model of rainbow trout movement and survival downriver from Lees Ferry (trout routing model), and (3) a model of the response of humpback chub population dynamics in the Little Colorado River and Colorado River to monthly mainstem temperatures and monthly trout abundances. The model of the Lees Ferry rainbow trout population dynamics is similar to previous models used for the Glen Canyon reach. The trout movement and humpback chub models, on the other hand, were developed for this application to reflect recent advancements, with an emphasis on deriving parameter values from data. The following paragraphs give a brief overview of the three submodels, with more detailed descriptions of each submodel available in subsequent sections (Sections F.3.1.1, F.3.1.2, and F.3.1.3).

Output from a flow model drives the Lees Ferry rainbow trout submodel. This model can be run independently from the trout routing and humpback chub submodels, as it does not include any feedbacks. Simulations include interannual variability in recruitment, outmigration, and growth based both on regression-derived predictions and variation around these predictions. Simulations also include parameter uncertainty, which includes a critical uncertainty related to the effectiveness of TMFs. The parameter associated with the critical uncertainty was fixed at two values (0.10 and 0.50) encompassing a hypothesized range of effectiveness, while all other parameters were drawn from the multivariate distribution estimated from data. Outputs from this submodel include four performance metrics, including simulated outmigration, which was used as an input to the trout routing submodel.

The trout routing submodel includes a single biological parameter describing movement, as well as multiple inputs related to implementation of mechanical removal, all of which are fixed. The trout routing submodel model is run a year at a time, after which it passes monthly rainbow trout abundances to the humpback chub submodel.

The humpback chub submodel simulates the impacts of rainbow trout and temperature (forecasted by a temperature model) on humpback chub population dynamics at a monthly time step. It returns the adult population abundance at the end of the year, which is used as one of the performance metrics and is also used by the trout routing model to determine if mechanical removal would be triggered in the next year. The humpback chub submodel includes parametric uncertainty including levels for a critical uncertainty related to the effect of rainbow trout on humpback chub survival and growth, as well as variation in other parameters. The humpback chub submodel also includes interannual variability in recruitment and outmigration.

More detailed information about each of the submodels is provided in the following sections.

F.3.1.1 Glen Canyon Trout Submodel

An age-structured population dynamics model was used to predict the abundance and growth of rainbow trout in Glen Canyon and the number of those fish that migrate into Marble Canyon. The model makes predictions on an annual time step for ages 1–6 yr. Annual recruitment, which was defined as the number of age-0 fish (i.e., fish hatched in the current year) that enter the population in a given year, is predicted based on flow statistics, and growth is predicted as a decreasing function of overall rainbow trout abundance. Abundance, in combination with age-specific angling vulnerabilities, is used to make predictions of angler catch per hour of effort. Predicted abundance and size distributions are used to compute the number of high-quality fish (trout ≥16 in. total length) potentially available for capture. The number of fish migrating from the Glen Canyon reach into Marble Canyon each year (out-migrants) is predicted as a proportion of the previous year's recruitment, and is used to determine the potential number of fish that eventually migrate down to the confluence of the Little Colorado River (RM 61), where their effects on humpback chub are simulated. Basic simulation parameters and those for key functional relationships were derived or fitted to values from the Korman et al. (2012) stock synthesis model. This model used 21 years of electrofishing-based catch-per-effort data for Glen and Marble Canyons, in conjunction with length frequencies and other information, to estimate annual recruitment, survival rate, von Bertalanffy growth parameters, and outmigration patterns (numbers, size, and timing). Specifics of the Glen Canyon trout simulation model are provided below.

Recruitment

The annual recruitment of age-0 trout in Glen Canyon was predicted based on a multiple linear regression driven by flow-derived independent variables. The model predicted log annual recruitment as a function of annual Glen Canyon Dam release volume, the range in mean daily flows during the critical early life history rearing period (May–August), and the presence of a spring HFE in each year or in the previous year (Korman et al. 2011c; Avery et al. 2015). The model explained 55% of the annual variation in the recruitment estimates from the Korman et al. (2012) stock synthesis model between 1990 and 2010 (Figure F-1). The flow-dependent regression model predicted that recruitment would be higher in years with greater annual volumes, reduced daily variation in flow between May and August, and when spring HFEs occur. In the simulation model, log recruitment each year is predicted from a random normal distribution, with the mean determined by linear regression parameters and hydrologic statistics, and the extent of error determined by the residual error in the regression model.

Recruitment for a given year was predicted to be higher if a spring HFE occurred in that year or in the previous year, based upon empirical relationships reported by Korman et al. (2011c). However, there is insufficient information to draw a conclusion about whether HFEs that occur in the fall would have a similar effect on recruitment of trout. The model considered this uncertainty about the effect of fall HFEs on recruitment of rainbow trout in the Glen Canyon reach by examining two hypotheses: (1) fall HFEs would have no effect on recruitment and (2) recruitment would increase at the same rate as seen with spring HFEs, but for only one year instead of two.

As described in Section 2.3.3.2 of the DEIS, TMFs are a special type of fluctuating flow designed to reduce the recruitment of trout by disadvantaging young-of-the-year (YOY) trout. TMFs have been proposed and developed on the basis of research described in Korman et al. (2005). TMFs are included as elements of some alternatives evaluated in the LTEMP DEIS, and the Glen Canyon trout submodel incorporated the ability to consider the effects that occurrence of TMFs could have on trout resources. For alternatives and associated long-term strategies that included TMFs, these flows were triggered in the model during years in which the initial production of YOY rainbow trout (based on hydrologic characteristics) in the Glen Canyon reach was anticipated to be greater than 200,000 individuals. Because there is uncertainty regarding how effective TMFs would be at disadvantaging YOY trout, the model was used to evaluate two different levels of effectiveness by reducing the number of YOY trout surviving to age-1 by either 10% or 50% for each 20-year simulation period.

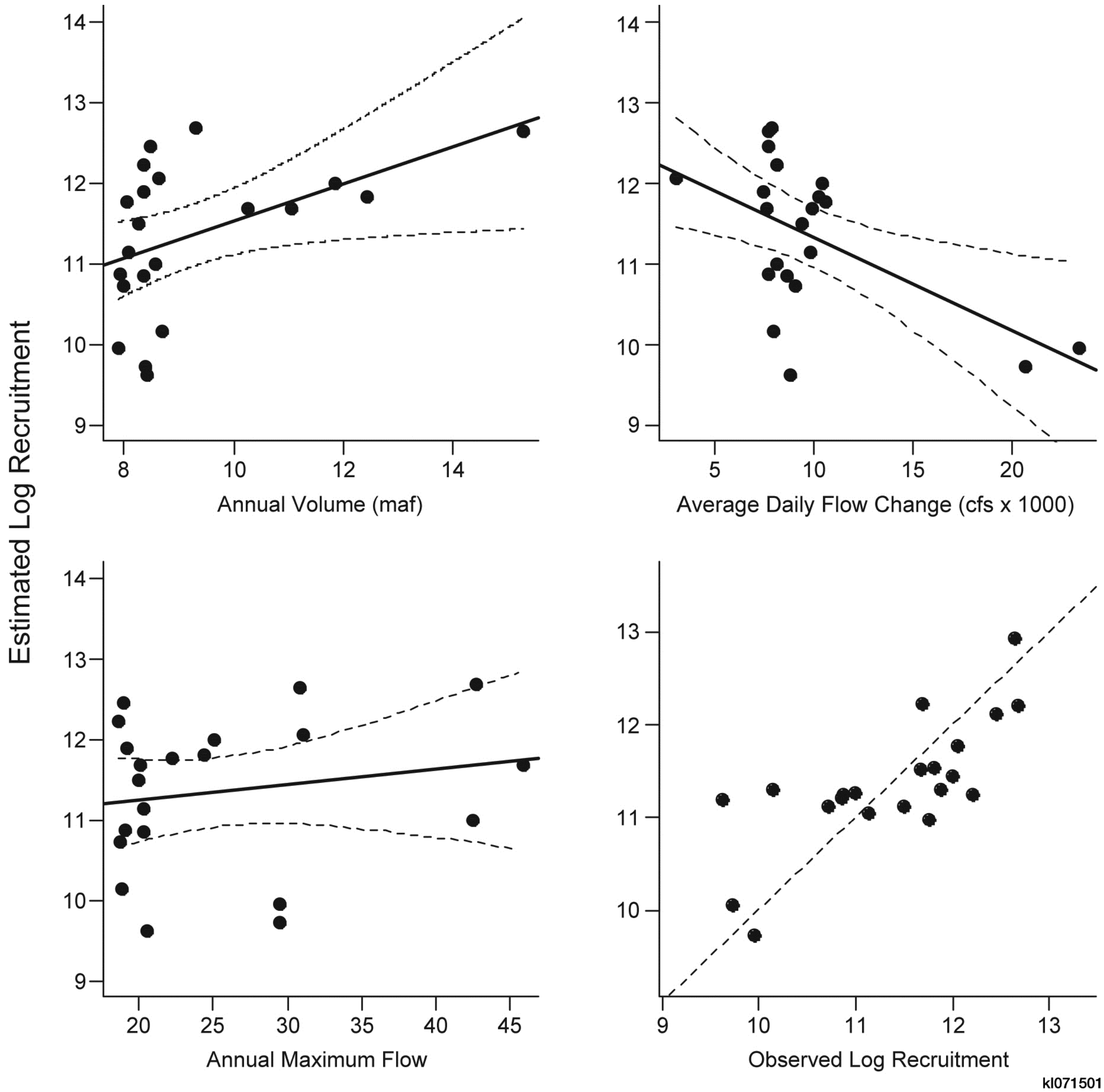


FIGURE F-1 Fit of Regressions Predicting the Log of Recruitment of Rainbow Trout in the Glen Canyon Reach Estimated by the Korman et al. (2012) Stock Synthesis Model as a Function of the Annual Release Volume from Glen Canyon Dam (million acre-feet), the Range of Mean Daily Flows during May–August (thousand cfs), and the Maximum Flow (cfs) Each Year (The bottom-right plot compares the overall fit of a multiple regression model with annual volume and range of mean daily flows during May–August as independent variables, and with the maximum annual flow independent variable replaced with a dummy variable with values of 1 for years prior to or with spring HFEs. The dashed line in the bottom-right graph indicates the 1:1 relationship and the 95% confidence interval in other graphs. The multiple regression model explained 55% of the variation in log recruitment and was statistically significant [p = 0.002].)

Growth

Length-at-age was calculated assuming a von Bertalanffy relationship that depends on the Brody growth coefficient ($vbK = 0.55$), the asymptotic length (L_{inf}, size at the terminal age), the coefficient of variation in length-at-age ($cvLen = 0.1$), and the mean size at age 1 ($L_0 = 130$ mm). Parameter estimates were derived from the stock synthesis model, which was fit to length-frequency and supplemental growth data (Korman et al. 2012, 2011a,b). Annual variation in asymptotic length was predicted as a linear function of the abundance of trout >150 mm. This model predicts only 18% of the annual variation in the annual asymptotic length estimates from the stock synthesis model (Figure F-2). To simulate interannual variation in L_{inf} in the model, annual deviates of L_{inf} in log space were added to a base value (5.89). In the simulation, predicted deviates from the $L_{inf} - N > 150$ regression model were added to the base value, and these formed the mean of a random normal distribution with a standard deviation equal to the residual error of the regression model.

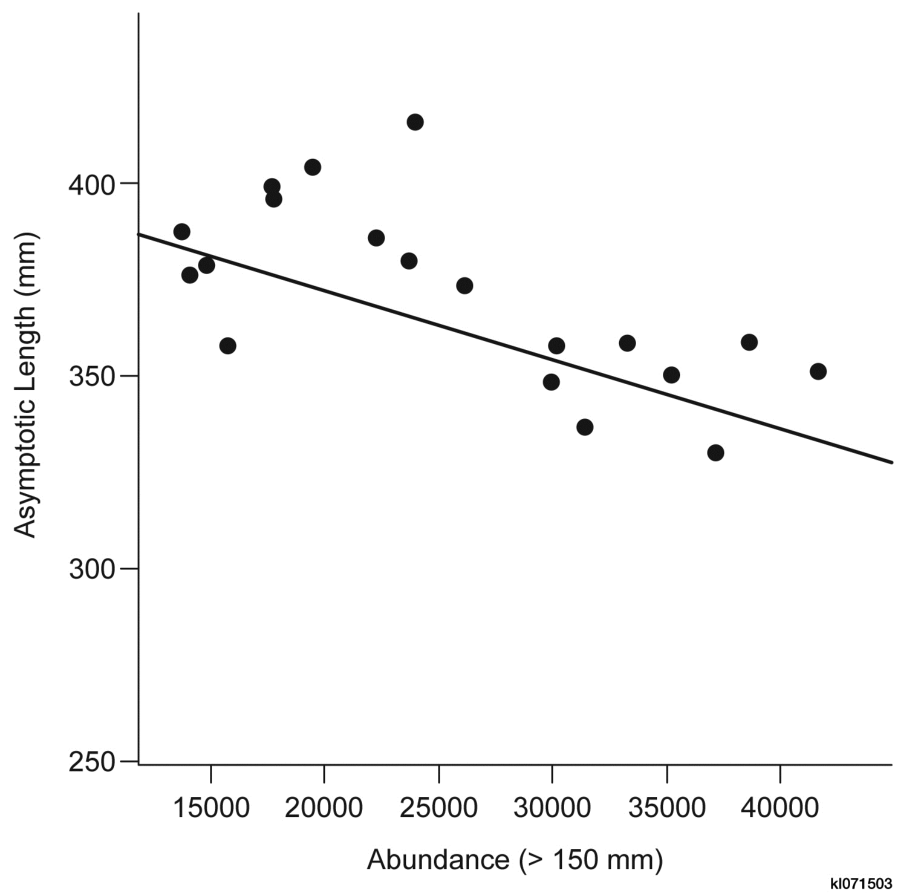


FIGURE F-2 Relationship between Annual Estimates of the Asymptotic Length of Rainbow Trout in Lees Ferry Predicted by the Stock Synthesis Model as a Function of the Estimated Abundance for Fish >150 mm (approximately age 1+) Each Year (The solid line is the best-fit relationship. This relationship explained 18% of the annual variation in asymptotic length and was not statistically significant [p = 0.056].)

Performance Metrics from Glen Canyon Trout Submodel

Four performance metrics were derived from the trout submodel in order to evaluate the relative degree to which the various alternatives would achieve a healthy high-quality recreational trout fishery in Glen Canyon National Recreation Area and reduce or eliminate downstream trout migration consistent with National Park Service fish management and Endangered Species Act (ESA) compliance needs. These four trout performance measures were:

1. Glen Canyon trout abundance index (for age 1+ fish)

2. Catch rate index (#/hr) for age 2+fish

3. Number of trout >16 in. total length

4. Trout emigration estimate (number of age-0 trout moving into Marble Canyon from Glen Canyon)

The Glen Canyon trout abundance index was calculated as the average of modeled annual abundance of trout that were 1 year of age or older during each 20-year simulation period. The model used an age-structured population dynamics model to calculate the annual abundance for age classes 1 through 6 based upon annual recruitment rates and density-dependent survival rates.

The catch rate index was calculated as the average annual angling catch per unit of effort (number of fish per hour) during the 20-year simulation period. Only fish 2 years of age or older were considered vulnerable to angling. The annual angling catch per effort in the fishery (CPE_{yr}) was predicted as the sum of products of an overall catchability coefficient ($q = 4.25e^{-05}$), age-specific vulnerabilities ($V_1 = 0$, $V_2 = 0.5$, and V_3 *to* $V_6 = 1$), and the predicted age-specific abundance for the year ($N_{yr,a}$):

$$CPE_{yr} = \sum_{a=0}^{6} \left(q \times V_a \times N_{yr,a} \right)$$

To estimate q, the simulation model was run using the recruitment estimates from the stock synthesis model to predict age-specific abundance between 1990 and 2010. The value for q was then calculated from the back-transformed average of the log of the ratio of the observed CPEs to the estimates of the vulnerable population each year. Thus, q represents the average scalar required to convert predicted vulnerable abundance to the observed CPE.

In order to evaluate the potential for large trout to be present in the population under a given alternative, a performance metric was calculated as the average of the annual modeled number of fish equal to or greater than 16 in. that would be present in the Glen Canyon reach. The number of trout in the population with total lengths equal to or greater than 16 in. during a given year was predicted as the sum of the products of the abundance-at-age and the proportion of the age with lengths greater than or equal to 16 in. That proportion meeting the length criterion is predicted based on a normal distribution (*pnorm*) with a mean predicted by expected length-at-age ($Len_{yr,a}$) determined using the von Bertalanffy relationship and a standard deviation determined by the coefficient of variation in length-at-age (*cvLen*):

$$N_{qual,yr} = \sum_{a=0}^{6} \left(N_{yr,a} \times pnorm\left(16, Len_{yr,a}, cvLen \times Len_{yr,a}\right)\right)$$

The trout emigration performance metric was calculated as the average of the annual modeled number of trout migrating from Glen to Marble Canyon during a 20-year simulation period. The Glen Canyon Trout submodel computes the number of trout migrating to Marble Canyon as a fraction of the recruitment estimate from the previous year (Figure F-3). A linear model with a zero intercept explained about 70% of the estimated outmigration from Korman et al. (2012). The model predicts that on average, the number of out-migrants is 42% of the recruitment value from the previous year; however, there is considerable interannual variation in this percentage (95% of values are between 0 and 91%). A normal distribution (*rnorm*) with a mean equal to the mean of the logit-transformed annual proportions and a standard deviation equal to the standard deviation of the transformed proportions was used to simulate the proportion of fish out-migrating in each year of the simulation. The back-transformed proportions were then multiplied by the previous year's recruitment ($Rec_{\text{yr-1}}$) to calculate the out-migration each year:

$$Out_{yr} = Rec_{yr-1} \times \text{logit}(rnorm(\text{mean} = –0.35, \text{sd} = 1.65))$$

Parameter estimates for the key linear models (recruitment-flow, out-migration-recruitment, asymptotic length-abundance) were estimated by linear regression. The variance-covariance matrices for these models, which represent the extent of uncertainty in parameter estimates and their covariation, were used to generate 1,000 different parameter values for each relationship. The simulation model integrated over these values to incorporate uncertainty in key functional relationships when making predictions for any long-term strategy and hydrologic trace.

In addition to the performance metrics that were used to evaluate the potential effects of alternatives and long-term strategies on the trout fishery and downstream migration of trout, the trout submodel also kept track of the number of TMFs expected to be triggered during each 20-year simulation period. The number of TMFs during a 20-year period was used as one indicator of how American Indian Tribes, some of which consider lethal actions to fish an adverse effect if there is no beneficial use, could be affected by alternatives and long-term strategies (see Appendix I) rather than a measure of effects on the trout fishery itself.

Evaluation of Trout Submodel

Annual flow statistics for Glen Canyon Dam were computed from the historical record between 1990 and 2010 and used as input to the Glen Canyon trout model to compare predictions with observations and best estimates of key state variables such as recruitment,

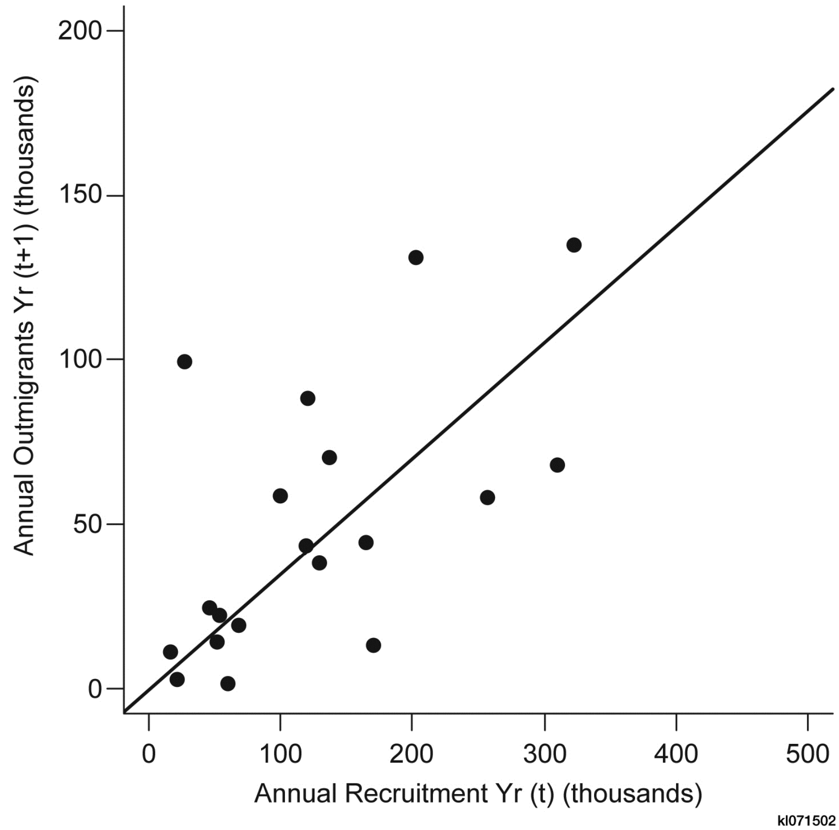


FIGURE F-3 The Relationship between Annual Recruitment of Rainbow Trout in Lees Ferry Estimated by the Korman et al. (2012) Stock Synthesis Model and the Number of Trout That Emigrate from Lees Ferry into Marble Canyon the Following Year (The solid line represents the best-fit relationship, which assumes no out-migration when there is no recruitment in the previous year [i.e., the line is forced through the origin]. This relationship predicted 72% of the annual variation in estimated out-migration and was statistically significant [$p < 0.001$].)

out-migration, and size at the terminal age. Predictions of angler CPE were compared to estimates of annual CPE from the Arizona Game and Fish Department (AZGFD) creel survey (Makinster et al. 2011). Simulations were based on most likely parameter estimates from the key regression models (recruitment-flow, outmigration-recruitment, asymptotic length-abundance) and did not include interannual variation in predictions to facilitate comparisons of predictions and data. Predictions of abundance were compared to the interannual trend in AZGFD electrofishing surveys. Other predictions (recruitment, asymptotic length, and out-migration) were compared to best-fit estimates from the Korman et al. (2012) stock synthesis model.

The historical flow-driven predictions of recruitment made by the simulation model produced an interannual trend quite similar to the estimates produced by Korman et al. (2012; Figure F-4, top-left panel). However, the model substantially over-predicted recruitment in 1996 and under-predicted recruitment in 2007–2009. The effects of high annual volumes and spring floods on recruitment may be confounded with other variables in the multiple regression model due to the low frequency of these events in the period of record.

The trend in predicted abundance from the model generally matched the trend in electrofishing-based CPE (Figure F-4, middle-left panel). The model over-predicted abundance in 2005–2007, perhaps because it did not account for a number of unusual events in earlier years that likely affected recruitment and adult mortality (e.g., a sudden change in minimum flow due to an emergency shutdown of Glen Canyon Dam generators, very few spawners in 2006, mortality of adults due warm water and low dissolved oxygen in releases during the fall of 2004). The trend in asymptotic length predicted by the model did not provide a good fit to the trend from the Korman et al. (2012) stock synthesis model. This is not surprising, as trout abundance was a relatively poor predictor of asymptotic length (Figure F-3), especially in years when other factors (e.g., low food availability, high mud snail abundance) appeared to have strong effects. Factors such as food availability and quality and long-term trends in reservoir productivity are likely more important drivers of growth than abundance.

The model was only partially able to reproduce the observed trend in angling CPE (Figure F-4, top-right). It correctly predicted an increase with abundance between 1992 and 1997. However, observed CPE for the following 3 years was relatively stable, while model predictions indicated that CPE increased by about 3-fold. As the model provided a relatively good fit to the observed trend in electrofishing CPE over the majority of the historical period, this likely indicates that catchability (q) declined beginning in 1999. Possible mechanisms include a reduction in q at higher trout densities, as a greater fraction of fish use less vulnerable habitats, or reduced q at lower flows (which began in 1999). The predicted number of quality-sized fish in the population (dashed line, top-right) has been low over the entire historical period (<1000) and declined from maximum values at the start of the period due to increasing abundance (top-left), which reduced asymptotic length (bottom-left).

The trend in simulated out-migration estimates was reasonably close to the historic trend estimated by the stock synthesis model (Figure F-4, lower-right). The proportion of recruitment that out-migrates each year is not constant (Figure F-2), and this simplification in the application of the simulation model to historical data leads to some of the error in out-migration estimates. Departures between the best recruitment estimates (Korman et al. 2012) and those derived from the flow regression (Figure F-4, top-left) increases the extent of error in out-migration estimates.

F.3.1.2 Trout Movement Submodel

One component of the LTEMP trout/humpback chub simulation model is the movement of rainbow trout from Glen Canyon to near the confluence of the Little Colorado River. The trout movement model predicts the monthly abundance of trout within each mile segment of the Colorado River from RM 0 to RM 150 and reports monthly abundance over broader river reaches as required for the humpback chub population dynamics model. While the LTEMP Rainbow Trout-Humpback Chub model is not focused on locations below approximately RM 66, the trout movement model extends below this location to avoid problems with modeling boundary conditions near the Little Colorado River. Key inputs to the trout movement model

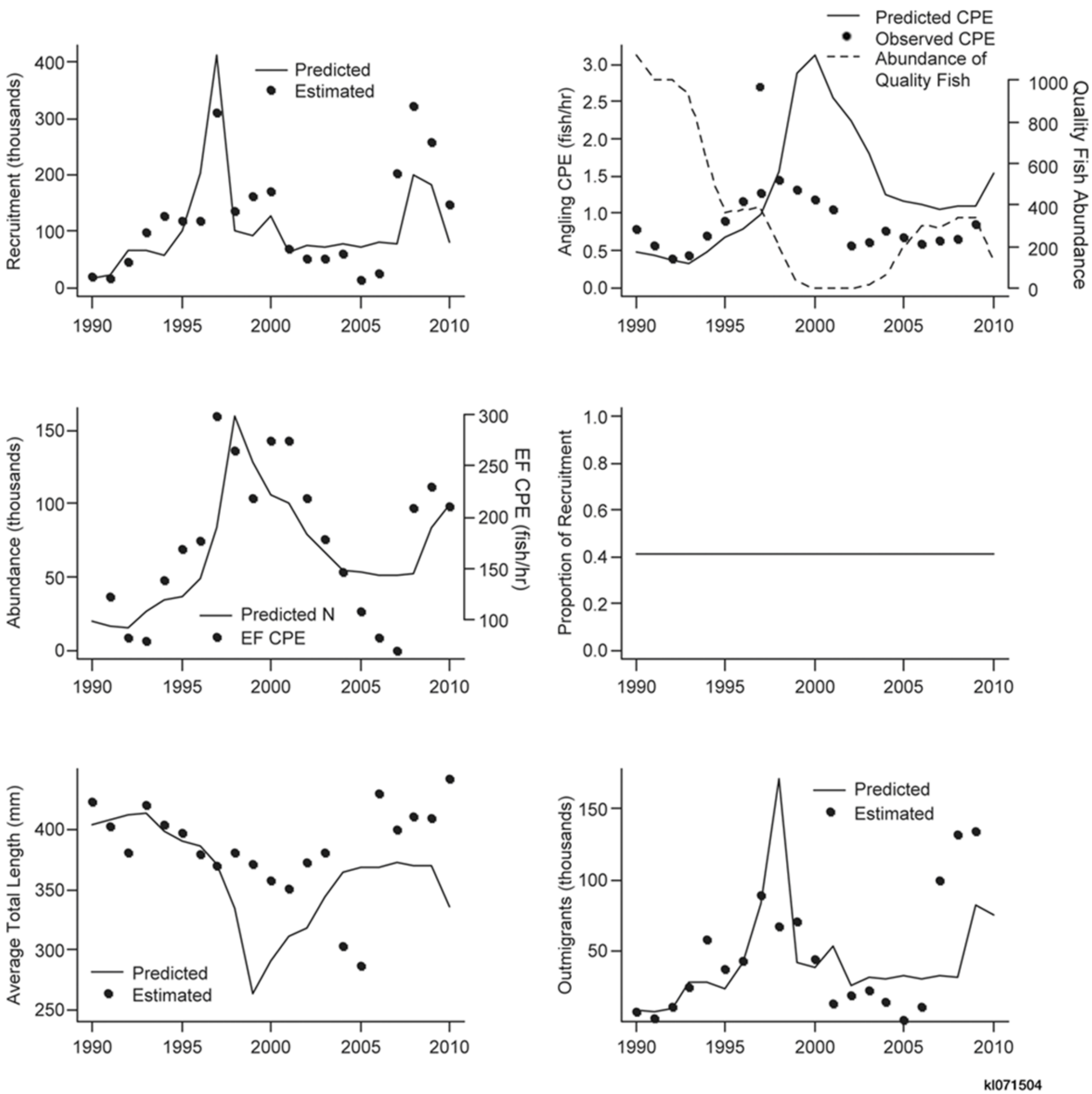


FIGURE F-4 Fit of the Glen Canyon Rainbow Trout Simulation Model to Predictions of Recruitment (top left), Asymptotic Length (bottom left), and the Number of Out-migrants (bottom right) Predicted by the Korman et al. (2012) Stock Synthesis Model (Also shown is the predicted abundance relative to catch per effort [CPE] from AZGFD electrofishing surveys [middle left], the predicted angling CPE compared to AZGFD creel survey estimates [top right], and the average proportion of recruitment that migrates from Glen to Marble Canyon each year [middle right].)

include the monthly number of age-0 trout out-migrating from the Glen Canyon reach, parameters that control the movement and dispersion of rainbow trout in Marble/Grand Canyons, the natural mortality rate of rainbow trout, and the number, intensity, and timing of nonnative mechanical removal trips conducted each year. The rules governing the implementation of mechanical removal were specified based on the Biological Opinion on nonnative fish control (Reclamation 2011b). Monthly movement and dispersion do not depend on trout density and are modeled as a random process following a Cauchy distribution of movement distances. To allow parameter estimation and to evaluate the ability of the model to reconstruct historic trout abundance patterns, model-predicted catch of rainbow trout from sampling efforts in 2000–2009 was compared to the observed catch.

The trout movement model accounts for the abundance of rainbow trout at a monthly time step and in one-mile-long river segments (RM segments) from RM 0 to RM 150. The age and size structure of the population was not modeled, although all immigrants from Glen Canyon are assumed to be YOY. At the end of each month, trout within each RM segment are diminished by some survival rate and then distributed to other RM segments according to a RM segment-specific movement distribution. This calculation is accomplished via matrix operations as:

$$\mathrm{n}(t+1) = \mathrm{MSn}(t),$$

where n is a vector containing the abundance of rainbow trout within each RM segment, M is the movement matrix specifying how the abundance at a particular RM segment is distributed to other segments, S is the survival matrix where the diagonal contains the survival of fish within each RM segment and all other elements are zero, and t is the month of the year.

Number of Trout from the Glen Canyon Reach

The number of fish entering the upstream-most RM segment in the model (RM 1) each month equals the number of annual emigrants calculated by the Glen Canyon trout submodel. The monthly number of trout entering the reach was assumed to be 1/12 of the annual total emigrants, as migration timing was assumed to be uniform across months.

Survival

Instantaneous natural mortality rate (M = 0.49/year) was assumed to be temporally and spatially constant and corresponded to a monthly survival rate of 0.96 based on mark recapture-based methods from the Natal Origins project (Korman et al. 2015). In the RM segments RM 56 to RM 66, monthly survival is also potentially influenced by mechanical removal operations. Survival rate associated with mechanical removal was modeled as:

$$MR_{surv} = (1-p),$$

where MR_{surv} is survival from mechanical removal, p is the electrofishing capture probability, and D is the number of times fish are removed from each RM segment (number of passes). Thus monthly survival rate in RM segments where mechanical removal is not conducted was 0.96, and in RM segments where mechanical removal was conducted, it was $0.96 \times MR_{surv}$. The diagonal elements of the survival matrix S contained these RM segment survival rates and non-diagonal elements were zero. Capture probability (*p*) was assumed to be 0.10, based on recent work from the Natal Origins project (Korman et al. 2015).

Mechanical Removal

Mechanical removal in RM 56–66 was triggered in a particular year when three conditions were simultaneously met: (1) mechanical removal was authorized under the alternative being modeled, (2) the estimated abundance of rainbow trout in the trigger reach (RM 63–64.5) during September of the previous year was greater than 760 individuals, and (3) the estimated number of adult humpback chub (from humpback chub submodel, see Section F.3.1.3) was less than 7,000 individuals. When the triggering conditions were met, mechanical removal was implemented as 6 removal trips that occurred from February through July. Occurrence of removal trips reduced the number of trout in the vicinity of the Little Colorado River during the month, based upon the abundance of trout and electrofishing capture probability estimated from past removal efforts.

Trout Movement

The movement of fish between RM segments was assumed to be a diffusion process in which the probability of a fish moving from each RM segment to every other RM segment followed a truncated Cauchy distribution. The distribution is said to be truncated as movement upstream of the RM 0 segment or downstream of the RM 150 segment was disallowed. The probability distribution for each RM segment was assumed to represent the proportions of fish that would move to every other segment and formed a row vector in a movement matrix.

Performance Metrics from Trout Movement Submodel

The principal purpose of the trout movement submodel was to provide inputs to the humpback chub population submodel pertaining to monthly estimates of the number of rainbow trout that would be present in the vicinity of the Little Colorado River and to calculate the number of trout that would be removed by mechanical removal efforts. Although there were no aquatic ecology performance metrics generated, the trout movement submodel was used to calculate the numbers of years in which mechanical removal trips were triggered for each 20-year simulation, and that calculation was used as an indicator of how Tribal resources could be affected by alternatives and long-term strategies (see Appendix I).

Two factors must coincide to trigger mechanical removal trips in the submodel: (1) there must be more than 760 adult rainbow trout projected for the test reach in the vicinity of the Little Colorado River confluence (RM 63–RM 64.5) and (2) the projected adult humpback chub population must be less than 7,000 individuals. The number of adult humpback chub is calculated by the humpback chub population submodel and provided as input to the trout movement submodel. Once triggered, the model assumes that 6 mechanical trip passes would occur during the year.

Estimating Model Parameters and Evaluating Model Predictions

Rainbow trout electrofishing catch data from 2000 through 2009 and between RM 0 and RM 65.7 were used to estimate the Cauchy scale distribution parameter and the catchability coefficient (q). These data were composed of the annual electrofishing catch and effort by the 10-mi reaches between RM 0–50 and by the reaches RM 50–61.5 and RM 61.5–65.7 (Makinster et al. 2011). The annual predicted catches (C_i) for each reach (i) were computed as:

$$C_i = n_i \times E_i \times q,$$

where n_i is the model-predicted abundance of rainbow trout within reach i during the month of June and E_i is AZGFD electrofishing effort in June.

The observed catch was assumed to be distributed as a Poisson random variable with mean equal to the model-predicted catch. Estimation of the Cauchy scale (γ = 3.38) parameter and the catchability coefficient ($q = 3.4e^{-06}$) was accomplished via the method of maximum likelihood and the function "optim" within R (R Core Team 2013). These estimates provided a reasonably good fit to the data (Figure F-5), providing confidence that the simulation model would accurately portray movement dynamics of rainbow trout. A more complex parameterization of the Cauchy distribution was tested, where the location parameter (which specifies the most probable movement distance) was estimated as a free parameter. The maximum likelihood estimate of the location parameter was approximately 5.0 e^{-03} confirming that most fish do not change location on a monthly basis. A normal distribution also was considered to describe movement distance, but there was a better fit to the data using the Cauchy distribution. Additionally, the Cauchy distribution of movement implies a smaller probability of fish moving long distances within a month than the normal distribution (Figure F-6) and is more biologically reasonable, considering the observed movement of tagged trout (unpublished data, GCMRC database).

F.3.1.3 Humpback Chub Population Submodel

A size- and location-structured population dynamics model was used to predict the size of the adult population of humpback chub over time. The model assumes five size classes of humpback chub (40–99 mm; 100–149 mm; 150–199 mm; 200–249 mm; and >250 mm, which are named size class 1–5, respectively) and two locations (Little Colorado River and Colorado River) for a total of 10 "states" (where a state is a unique combination of size and location; for example, a fish in the Little Colorado River that is 40–99 mm is in state 1; Figure F-7). The structure of this model is based on recent modeling work (Yackulic et al. 2014) as well as a new set of candidate models developed specifically to address the effects of temperature and rainbow trout on humpback chub survival (see "Model Selection and Development" below). The model uses a monthly time step and assumes constant survival for all states except for state 6, corresponding to juveniles in the Colorado River. Survival for this state depends on rainbow trout abundance. Growth of size class 1 (40–99 mm) humpback chub depends on both water temperature and rainbow trout abundance. Growth for all other size classes in the Colorado River is temperature-dependent, while Little Colorado River growth is assumed constant. Movement

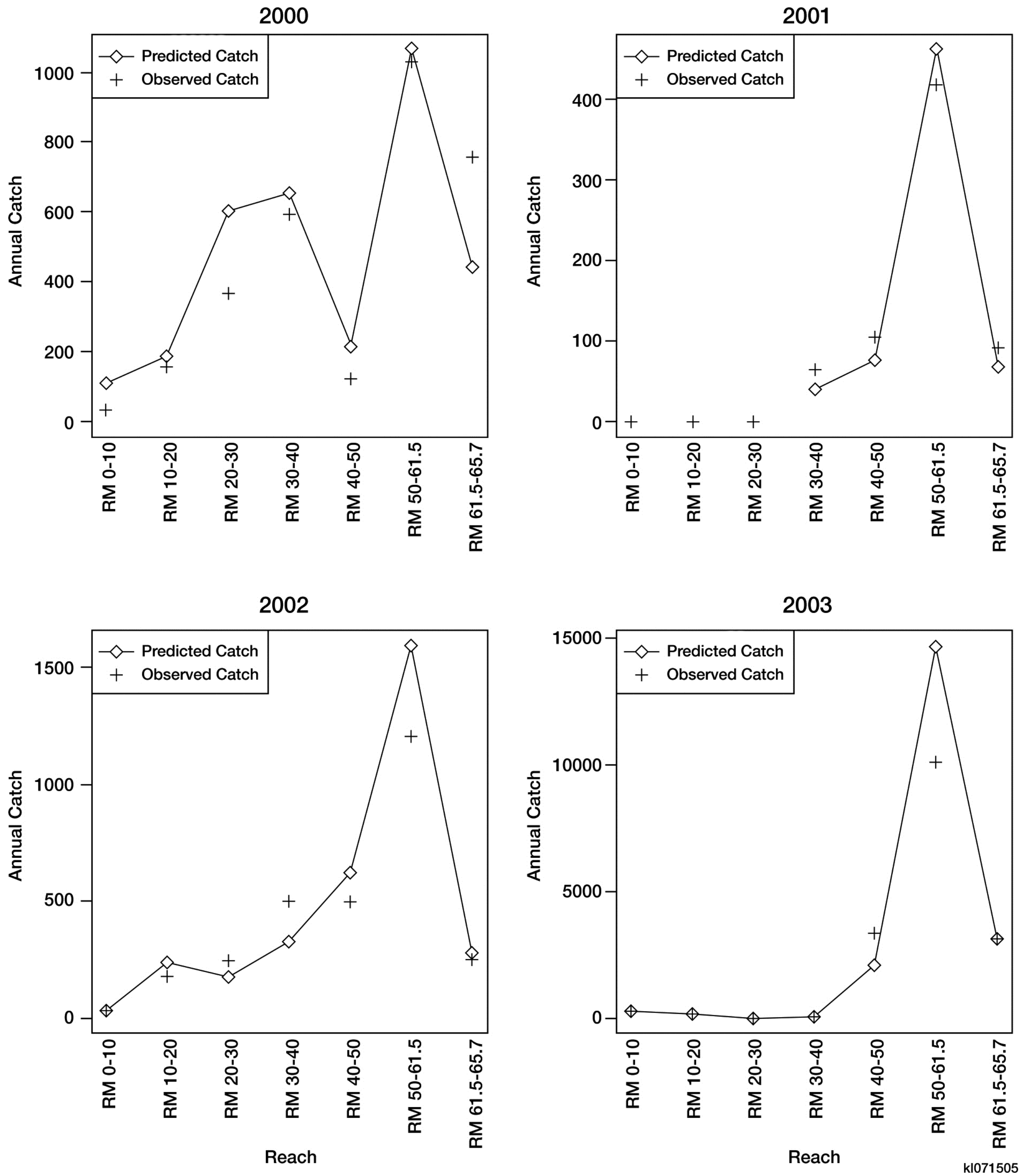
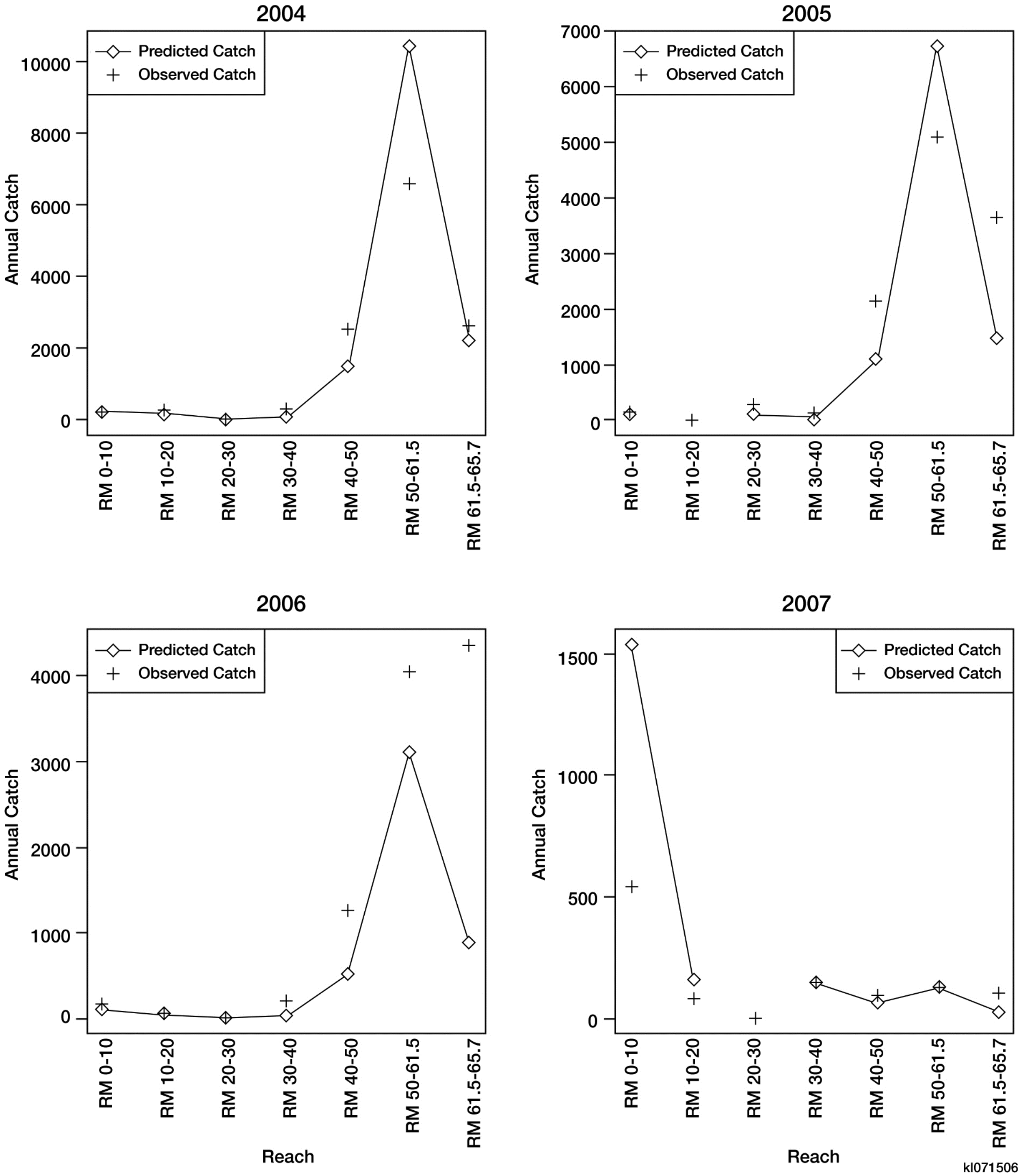


FIGURE F-5 Predicted and Observed Annual Catch of Rainbow Trout by Year and River Reach



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2 **FIGURE F-5 (Cont.)**

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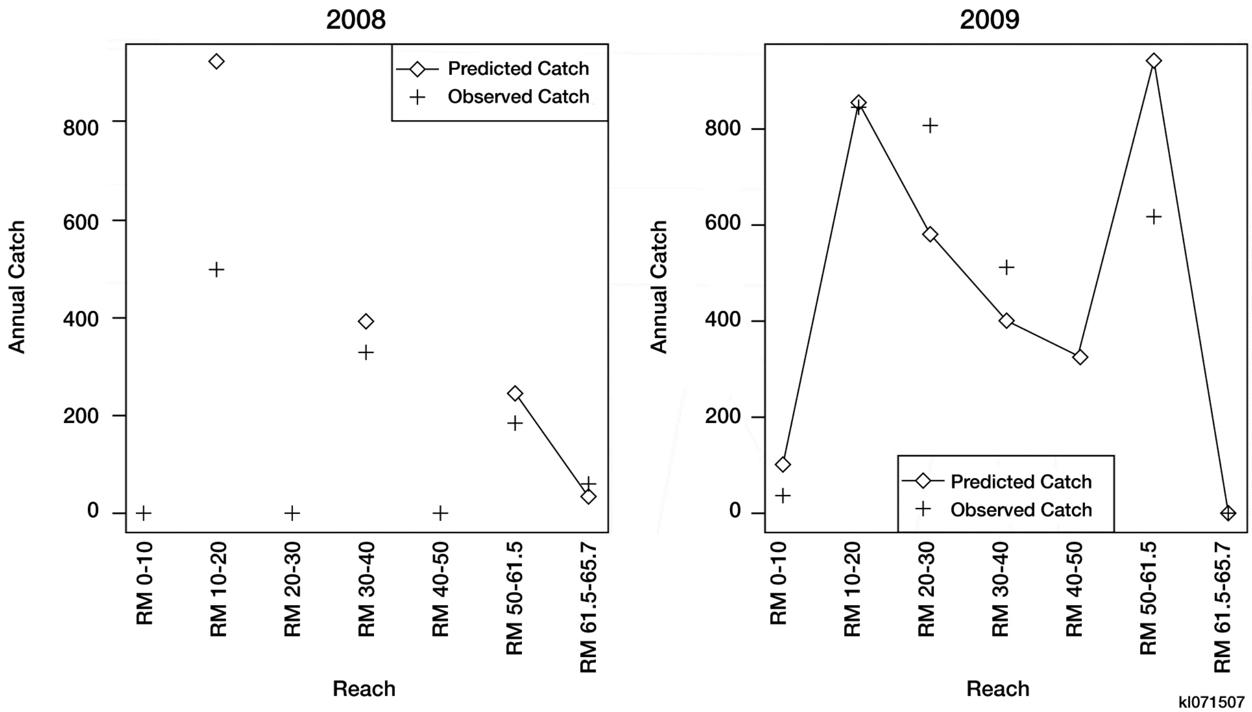

FIGURE F-5 (Cont.)

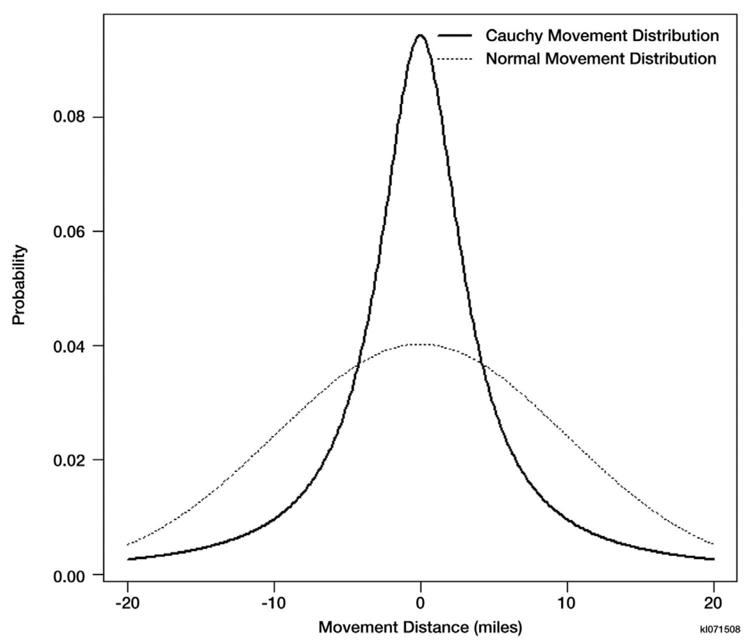

FIGURE F-6 Best-Fitting Distributions Describing Monthly Movement of Rainbow Trout in Marble Canyon Assuming Either a Normal or Cauchy Distribution (The Cauchy distribution implies a lower probability of large monthly movements and agrees better with movement observations from tagging data.)

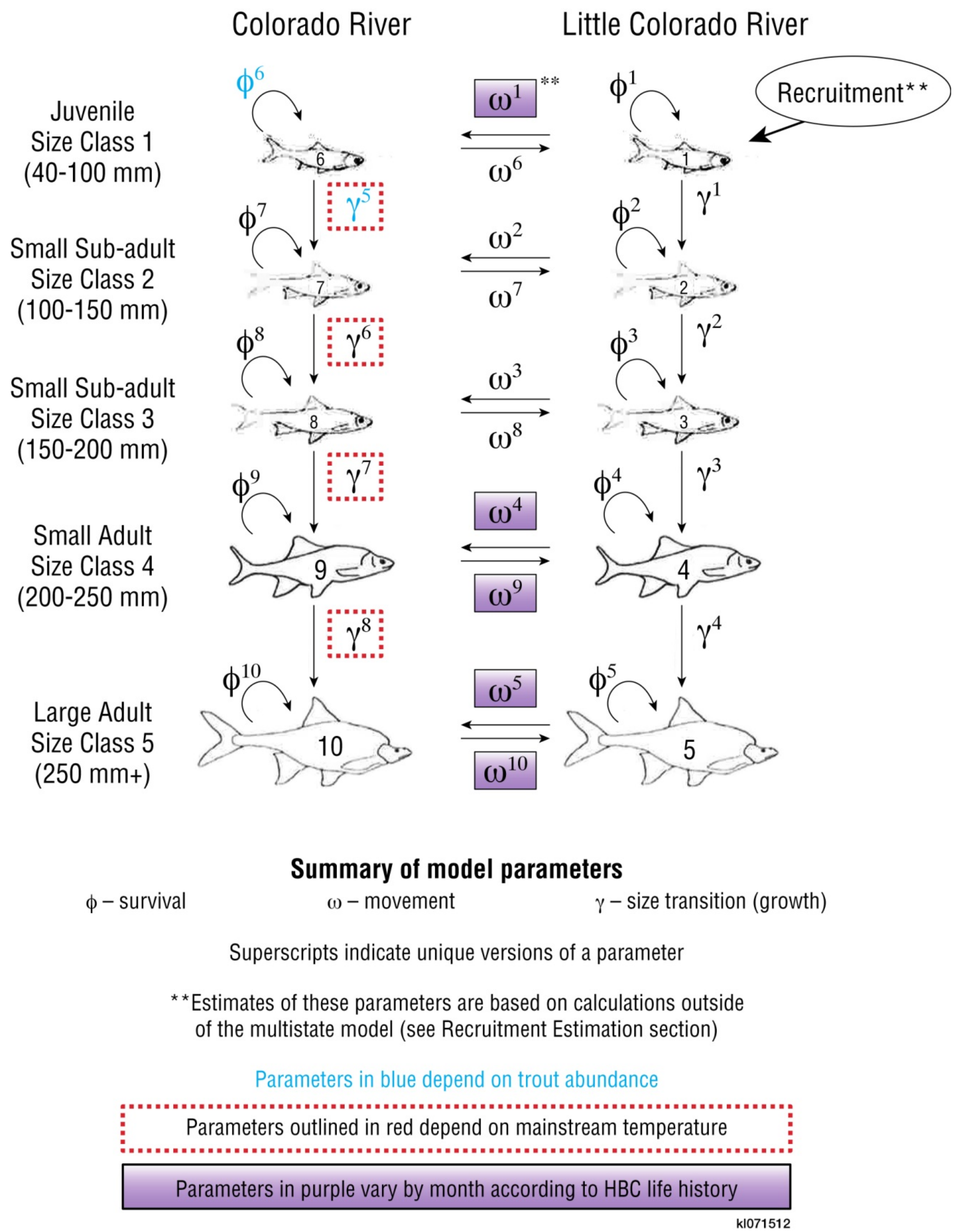

FIGURE F-7 Visual Summary of Humpback Chub Population Model Structure (The number on each fish represents its state number. Modified from Yackulic et al. [2014].)

between the Little Colorado River and Colorado River is modeled via movement parameters that vary depending on the month and size class (see Yackulic et al. 2014, for more details regarding movement parameters). In addition to parameters describing survival, movement, and growth, the simulation model also relies on estimates of the starting abundance in each of the 10 states, as well as assumed annual recruit abundance.

All YOY fish recruit to state 1 (i.e., size class 1 fish in the Little Colorado River) in July. Most parameters were estimated directly from data collected during 2009–2013 in the Colorado River and 2009–2012 in the Little Colorado River. Recruitment was approximated by comparison of estimated juvenile abundances in the Colorado River and Little Colorado River between 2009 and 2012. This analysis also led to modification of the value for the movement parameter associated with juvenile out-migration from the Little Colorado River (see "Recruitment Estimation" below). Yackulic et al. (2014) had previously speculated that this parameter might be biased, since July marking of juveniles has, until recently, been limited to a small section of the Little Colorado River proximate to the Colorado River that is likely to experience higher overall out-migration than the Little Colorado River as a whole. Recruitment estimates were also influenced by recent research suggesting severely diminished recruitment in years with little winter runoff in the Little Colorado River (Van Haverbeke et al. 2013).

Having estimated the maximum likelihood ("best") values of parameters based mainly on data collected from 2009 to 2013, the simulation model was run using a 20-year sequence of observed temperatures near the Little Colorado River between 1990 and 2009, as well as predictions of rainbow trout abundance for this period from the Glen Canyon and trout movement submodels. These outputs were compared to trends reported in Coggins and Walters (2009), as discussed in "Evaluating Model Predictions," below. Potential uncertainties in model predictions are discussed in "Model Uncertainties" below.

Model Selection and Development

The primary objective for the humpback chub population model was to estimate the effects of mainstem temperature and trout abundance on humpback chub population dynamics (i.e., growth and survival). Six candidate models that represent different *a priori* hypotheses concerning potential effects were evaluated:

- Model A: Rainbow trout and temperature have no effect on growth and survival.

- Model B: Survival of size class 1 humpback chub in the Colorado River is a logit linear function of rainbow trout abundance. Growth of all size classes in the Colorado River are logit linear functions of temperature with independent intercepts for each size class and a shared slope (a model with different slopes for each size class was considered, *a posteriori*, but this did not improve the fit considerably). Model B was based on the hypotheses that temperature is a primary control on growth rates and that rainbow trout mainly affect humpback chub by lowering the survival of juvenile humpback chub. This does not mean that rainbow trout effects are solely predatory, as competition with trout could lead to lowered survival if humpback chub were forced to forage longer or in suboptimal habitat, leading to increased predation risk by species other than rainbow trout.

- Model C: As in Model B, but growth of size class 1 fish is a function of rainbow trout abundance in addition to temperature. Rainbow trout are hypothesized to affect humpback chub growth by forcing them into suboptimal habitats and directly consuming food resources that might otherwise be consumed by young humpback chub. This effect is likely to be greatest in young fish because they are frequently found in nearshore environments that rainbow trout also prefer.

- Model D: As in Model C, but growth of size class 2 humpback chub is also a logit linear function of rainbow trout abundance in addition to temperature.

- Model E: As in Model B, but survival of size class 1 fish is a function of temperature in addition to rainbow trout abundance. Increased temperature is expected to increase the swimming ability of juvenile humpback chub, which should in turn aid them in avoiding predation by a variety of fish species in the system.

- Model F: A combination of Models C and E.

A general model structure modified from Yackulic et al. (2014) was used to fit a series of mark-recapture multistate models using maximum likelihood. For more technical details, see Yackulic et al. (2014). Yackulic et al. (2014) suggested three important features of humpback chub movement between the Little Colorado River and Colorado River:

1. Juveniles out-migrate from the Little Colorado River at a different and higher rate during July through September as opposed to the rest of the year,

2. Smaller and larger adults spawn at different rates, and

3. There is evidence for a resident Little Colorado River population.

The models that were considered include the first two of these elements, but ignore the third element. The third element is ignored because it would make simulations more difficult and is likely to only apply to a relatively small portion of the adult population (about 15%). Moreover, since the model only considers those fish that move into the mainstem, the movement dynamics of the system can be well represented without this detail.

Monthly temperatures were calculated using data from U.S. Geological Survey (USGS) gage 09383100 located on the Colorado River above the confluence with the Little Colorado River. Rainbow trout abundance in 2012 and 2013 was calculated by averaging trip estimates from the Natal Origins project within each year. Rainbow trout estimates for 2009–2011 were back-calculated based on the relationship between the catch between RM 63.4 and RM 64.8 and the estimated abundance in the same area.

Models were fit using general-purpose optimization algorithms provided by "optim" in R (version 3.0.2) using the BFGS (Broyden, Fletcher, Goldfarb and Shanno) method[1] and were run until convergence of all models was obtained. The variance inflation factor (c-hat) was calculated based on model F, and models were compared using the quasi-Akaike's Information Criterion (qAIC) calculation.[2] Model selection based on qAIC favored model C (summarized in Figure F-7), and estimates from this model were used for further steps. Figure F-8 illustrates the estimated relationships between temperature and trout and various survival and growth parameters. The maximum likelihood estimates from these relationships were used for backcasting, while combinations of the draws from the multivariate normal and critical uncertainties were used to characterize these relationships in simulations conducted for the comparison of LTEMP alternatives.

Recruitment Estimation

The one value needed for simulation that was not estimated in the model selection section is the mean annual recruitment, along with the variability around this mean. Annual recruitment is defined here as the number of YOY humpback chub present in the Little Colorado River in July. By July, most YOY are typically above 40 mm in total length. While some YOY will have left the Little Colorado River before this, several lines of evidence suggest that fish that leave the Little Colorado River before July do not contribute appreciably to population growth, given the temperature typically found in the Colorado River during May and June (Robinson and Childs 2001). Unfortunately, direct estimates of July YOY abundance in the Little Colorado River are not available. However, estimates from the Little Colorado River during September–October are available for 2001 through 2012 in Van Haverbeke et al. (2013), and were used here. The parameters estimated in the model should allow back-calculation of July YOY abundance in the Little Colorado River from the September abundance using the following formula:

$$N_J^1 = \frac{N_S^1}{\left[\emptyset^1\left(1-\omega_{JS}^1\right)\right]^2}$$

where N_J^1 is recruitment to state 1 in July, N_S^1 is recruitment to state 1 in September, ϕ^1 is the probability of survival during state 1 in the Little Colorado River, and ω_{JS}^1 is the probability of moving from the Little Colorado River to the mainstem Colorado River during the July-to-September period.

[1] For details regarding the "optim" function in the "stats" package for Program R, see http://www.inside-r.org/r-doc/stats/optim.

[2] For additional information, refer to http://www.inside-r.org/packages/cran/MuMIn/docs/QAIC.

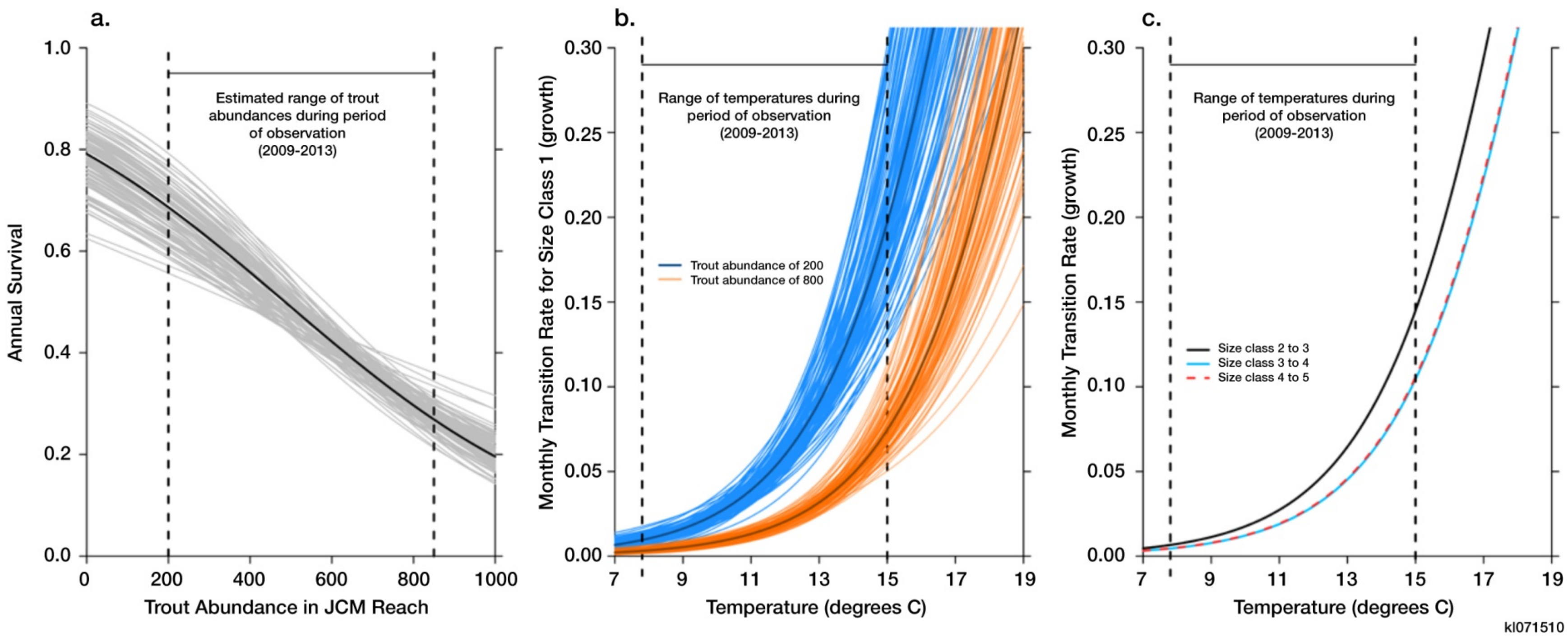

FIGURE F-8 Modeled Effects of Trout Abundance and Temperature on Humpback Chub Survival and Growth ([a] Annual survival of juvenile humpback chub [40–99 mm] declines relative to estimated trout abundance in the Colorado River; gray lines are based on 100 draws from a multivariate normal distribution based on maximum likelihood estimates and associated covariance matrix and give an indication of uncertainty around the maximum likelihood estimates in black. [b] Monthly size transition rates [proportional to growth] as a function of temperature with trout abundance set at either 200 or 800; as in panel [a], dark lines indicate best estimates and lighter lines are draws from a multivariate normal distribution giving an indication of uncertainty. [c] Dependence of size transition rates [growth] for larger fish on temperature. Note that relationships have a common slope but different intercepts. Uncertainty in these rates is comparable to the uncertainty around either of the curves in panel [b], with slightly more uncertainty around the intercept associated with the transition from size class 4 to size class 5.)

However, this approach is based on estimates of the monthly probability of size class fish moving from the Little Colorado River during the July–August and August–September intervals, ω_{JS}^{1}. Unfortunately, this is the parameter in the multistate model that is most likely to be biased because of details of sampling. In short, up until 2013, all July and August marking of humpback chub at the Little Colorado River was limited in its spatial extent to an area near the confluence, which is likely to have a higher rate of export than the Little Colorado River as a whole. Moreover, over two-thirds of the marked fish were marked in 2011 and 2012, years that exhibited large increases in the abundance of size class 1 humpback chub in the juvenile chub monitoring (JCM) reach, thereby suggesting higher export (see Yackulic et al. 2014, for a full discussion). Lastly, both July recruitment, N_{J}^{1}, and movement out of the Little Colorado River, ω_{JS}^{1}, may exhibit substantial interannual variability (in comparison to, say, adult survival), even though the limited number of marked fish released in July and August into the Little Colorado River in 2009 through 2012 does not allow us to estimate interannual variability in our models.

Therefore, a different approach was taken that is based on the estimated increase in size class 1 abundance in the JCM reach between July and September, as well as the estimated proportion of humpback chub in the JCM reach, τ, and survival rates in both the Little Colorado River, ϕ^{1}, and Colorado River, ϕ^{6}. (Note that humpback chub in size class 1 in the Colorado River are frequently two or more years old, whereas almost all size class 1 fish caught in the Little Colorado River in the fall are YOY fish). This approach involved solving the following equations for N_{J}^{1} and ω_{JS}^{1} for each year:

$$N_{J}^{1} = \frac{N_{S}^{1}}{\left[\emptyset^{1}\left(1-\omega_{JS}^{1}\right)\right]^{2}}$$

and

$$N_{J}^{1} = \frac{N_{S}^{6} - N_{J}^{6} \times \emptyset^{6} \times \emptyset^{6}}{\left(\emptyset^{1} \times \omega_{JS}^{1} \times \emptyset^{6} + \emptyset^{1} \times \left(1-\omega_{JS}^{1}\right) \times \emptyset^{1} \times \omega_{JS}^{1}\right) \times \tau}$$

This approach was applied to abundance estimates from 2009 to 2012 and resulted in estimated values of ω_{JS}^{1} of 0.15, 0.28, 0.45, and 0.52 (mean, 0.35), with associated values of N_{J}^{1} of 5,000, 17,000, 45,000, and 35,000 (mean, 25,000). Another aspect of recruitment highlighted in Van Haverbeke et al. (2013) is that in years with low runoff between January 1 and May 31, there appears to be weak recruitment, at least in terms of the number of YOY remaining in the Little Colorado River in the fall. Six years between 1990 and 2013 meet this criterion (1990, 1996, 1999, 2000, 2002, and 2006).

When backcasting historical trends, the mean values across years for both ω_{JS}^{1} and N_{J}^{1} were used, with the exception of “weak recruitment years” in which recruitment was assumed to be 2,500, based on an examination of estimates in Van Haverbeke et al. (2013). For forecasting, “weak” versus “strong” recruitment years were modeled as a Bernoulli process in which weak years occur with a probability of 0.25 (based on the observed frequency of these hydrologic conditions in the Little Colorado River from 1990 to 2013). For “strong” years, annual recruitment values were drawn from a uniform distribution between 0 and 50,000. For both "strong" and "weak" years, out-migration was chosen randomly from a uniform distribution between 0.15 and 0.55.

Performance Metrics from Humpback Chub Population Submodel

The resource goal identified for humpback chub is to "meet humpback chub recovery goals including maintaining a self-sustaining population, spawning habitat, and aggregations in the humpback chub's natural range in the Colorado River and its tributaries below the Glen Canyon Dam" (DEIS Section 1.4). The humpback chub population submodel was used to calculate an estimate of the number of adult (i.e., >200 mm total length) humpback chub that would be present in the aggregation associated with the Little Colorado River for each year of a 20-year simulation period. In order to evaluate and compare the potential for alternatives and long-term strategies to lead to extinction or improvement of the humpback chub population in the Grand Canyon, the modeled minimum number of adult humpback chub that would occur during each 20-year simulation period was used as the performance metric.

Evaluating Model Predictions

Humpback chub population dynamics were backcasted using maximum likelihood estimates of parameters (see "Model Selection and Development" section), with the exception of the parameters related to recruitment and juvenile out-migration from the Little Colorado River (see "Recruitment Estimation" section) and an initial vector of abundances by state. Initially dynamics were simulated using a monthly time step; however, based on concerns expressed by C. Walters, the time scale was coarsened to six-month intervals so as to minimize potential issues related to numerical diffusion. This was accomplished by calculating a six-month transition matrix and then removing any transitions of more than one size class and adding these to the cells corresponding to a one size class transition. The initial structure of the population was based roughly on estimates from 2009 to 2012. For the Little Colorado River, abundance by size classes 1–5 was 4,000, 2,500, 1,800, 1,200, and 800, respectively, while corresponding Colorado River abundances by size were 20,000, 7,000, 5,500, 4,000, and 5,000. The simulation model was also provided a 20-year sequence of observed temperature near the Little Colorado River between 1990 and 2009, as well as predictions of trout abundance for this period that resulted from the Glen Canyon trout and trout movement submodels (Sections F.3.1.1 and F.3.1.1, respectively). While the backcasted simulation (Figure F-9) suggests a later decline than the Age-Structured Mark Recapture (ASMR) estimates (Coggins and Walters 2009), followed by a quicker recovery, the patterns are remarkably similar, given that parameters from the simulation model were derived primarily from a more recent period (2009–2013). Moreover, the ASMR estimation method is known to have some biases (Coggins and Walters 2009), so minor discrepancies are expected.

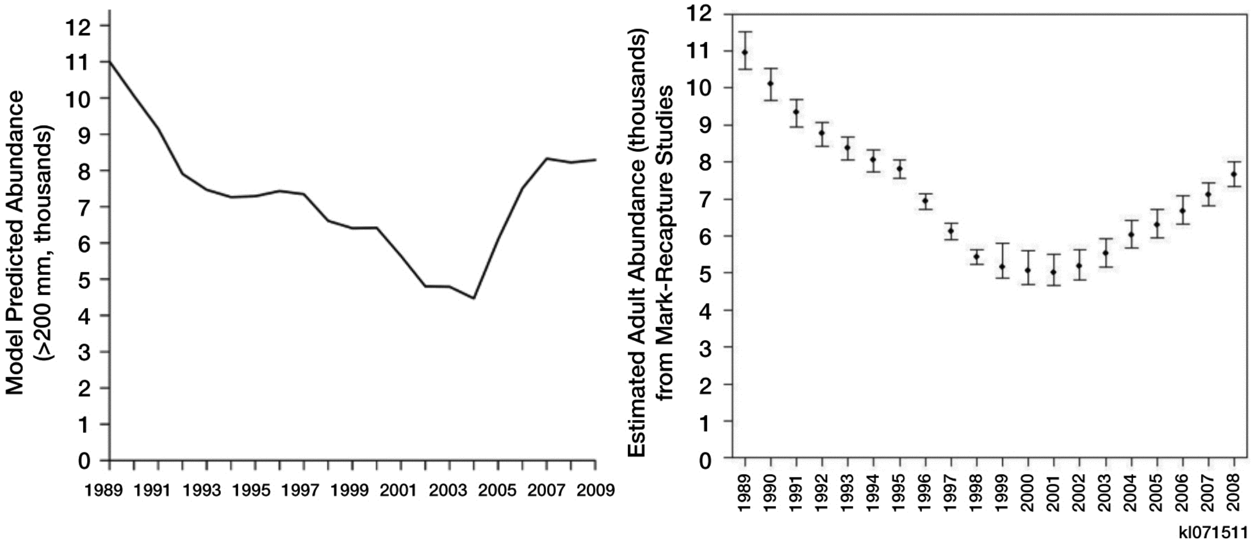

FIGURE F-9 Simulated Adult Abundances from Backcasted Model (left) Compared to Patterns Reported in Coggins and Walters (2009) (right)

Model Uncertainties

The model described here is based on the best available information and does a good job of backcasting the dynamics of humpback chub populations for a period of time (1990–2008) that is separate from the period of time (2009–2012) over which most parameters were estimated. However, like all models, it is only a representation of the actual system it seeks to describe. There are a number of conditions that could lead to dynamics in humpback chub populations that are different from those predicted with the model. Some of these conditions are listed here, in no particular order:

- No portion of this model explicitly models short- or long-term impacts of flows or temperature on the aquatic food base. Flow, particularly an increased frequency of flooding, has the potential to permanently change the composition of the invertebrate assemblage, as has been observed in other regulated rivers (Robinson 2012; see Section F.2). This shift could be beneficial for both rainbow trout and humpback chub resources, positive for one and negative for the other, or detrimental to both, and initial impacts may differ from long-term consequences. Similar, unpredictable shifts in the invertebrate assemblage could also occur because of long-term changes in release temperatures associated with climate change and lower Lake Powell reservoir elevations.

- Temperature–growth relationships estimated here are based on a relatively short period of record and do not consider seasonal patterns in food availability, light, and turbidity. As such, the humpback chub submodel assumes a temperature of 11°C (52°F) observed in clear water in June during midge emergence will lead to the same growth as a temperature of 11°C (52°F) in August in turbid water. Moreover, monthly mean temperatures at the Little Colorado River confluence from 2009 to 2013 peaked at roughly 15°C (59°F), suggesting that modeling the effects of substantially warmer temperatures on humpback chub populations represents an extrapolation. On the other hand, the model did a reasonable job of backcasting dynamics during the 1990–2009 era, even though monthly temperatures reached 16.7°C (62°F) in one year (2005).

- The humpback chub model does not consider the potential effects of other fish species besides rainbow trout that are already relatively common in the system and known to eat humpback chub (e.g., brown trout and various catfish species), nor does it attempt to account for the negative effects of other warmwater nonnative fishes that could become prevalent if temperatures above 16°C (61°F) become common. Potential effects of cannibalism by humpback chub are also not directly considered by the model.

- Climate change could lead to increases in the proportion of "weak" recruitment years in the Little Colorado River, particularly if winter precipitation in the Little Colorado River watershed becomes less frequent.

F.3.2 Results for LTEMP Alternatives

The results for the Rainbow Trout-Humpback Chub Model for each of the alternatives (including associated long-term strategies) are summarized in the following sections. Values for the means of the six metrics resulting from the model are summarized in Table F-8. The magnitude of effects to rainbow trout and humpback chub populations are estimated using the performance metrics identified in Sections F.3.1.1, F.3.1.2, and F.3.1.3.

F.3.2.1 Rainbow Trout Performance Measures

This section summarizes the results for the performance measures for rainbow trout that were derived from the Rainbow Trout-Humpback Chub Model.

Rainbow Trout Population Estimates

The rainbow trout population estimates for the 19 LTEMP alternatives and associated long-term strategies are summarized in Figure F-10. Among all of the long-term strategies evaluated, the modeled average abundance of age-1 (i.e., individuals that are 1 year old) and older rainbow trout during the simulations of 20-year LTEMP periods ranged from about 48,000 to 242,000 individuals in the Glen Canyon reach. Overall means (i.e., mean abundance for all simulations) for the various long-term strategies ranged from approximately 61,000 individuals under long-term strategy E6 to approximately 160,000 individuals under Alternative F

(Table F-8; Figure F-10). The differences among the modeled population levels for rainbow trout reflect the estimated levels of annual recruitment based on the empirically derived flow-dependent regressions in the model that predict that annual recruitment of rainbow trout will increase as a function of greater annual volumes, reduced daily variation in flow between May and August, the occurrence of spring HFEs, and implementation of management actions (i.e., TMFs) that would decrease annual survival of YOY trout (see "Recruitment" in Section F.3.1.1) in high-recruitment years. Table 4.1-1 identifies the experimental elements included in the various long-term strategies, and Appendix E of the DEIS describes the number and duration of HFEs that would be expected under the various long-term strategies.

Although there is a considerable amount of overlap in the ranges of the estimates for some long-term strategies, the overall modeled average rainbow trout abundance in the Glen Canyon reach was greatest under long-term strategies C2, C4, D3, F, and G. With the exception of long-term strategy G, all of these long-term strategies implement spring HFEs and would have steadier flows (at least for the May–August portion of the year) than Alternative A and would not include implementation of TMFs. Although Alternative G would include implementation of TMFs, the annual production of trout would be expected to be very high due to a high proportion

TABLE F-8 Summary of Metrics Values from the Rainbow Trout-Humpback Chub Model[a]

Alternatives and Long-Term Strategies	Trout Abundance	Number of Trout ≥16 in. Total Length	Catch Rates (fish/hr)	Number of Out-migrants (fish/year)	Number of Years with Trout Management Flows	Number of Years with Mechanical Removal	Minimum Humpback Chub Population
A	94,667	769	2.11	36,699	0.0	0.07	4,991
B1	74,078	867	1.67	29,586	3.0	0.44	5,392
B2	62,822	920	1.46	24,172	3.1	0.30	5,541
C1	102,342	748	2.23	43,683	6.5	0.00	5,016
C2	150,285	640	3.18	66,890	0.0	0.00	4,527
C3	85,181	830	1.90	33,559	0.0	0.74	5,335
C4	127,129	707	2.72	55,076	0.0	2.80	4,874
D1	92,854	811	2.02	40,784	3.9	1.67	5,247
D2	99,452	796	2.15	43,981	6.9	2.02	5,181
D3	123,448	711	2.63	55,811	0.0	2.95	4,876
D4	93,312	810	2.03	40,936	3.8	1.69	5,241
E1	87,812	826	1.93	37,614	2.6	0.00	5,269
E2	108,046	761	2.33	47,450	0.0	0.00	5,015
E3	73,727	891	1.68	28,499	0.0	0.47	5,477
E4	100,330	781	2.19	42,806	0.0	1.73	5,103
E5	73,848	890	1.68	28,561	0.0	0.00	5,470
E6	60,600	956	1.42	22,415	2.4	0.00	5,708
F	160,297	592	3.37	71,869	0.0	0.00	4,450
G	131,816	702	2.81	58,533	11.0	3.05	4,741

[a] Mean values for 63 modeled hydrology–sediment conditions.

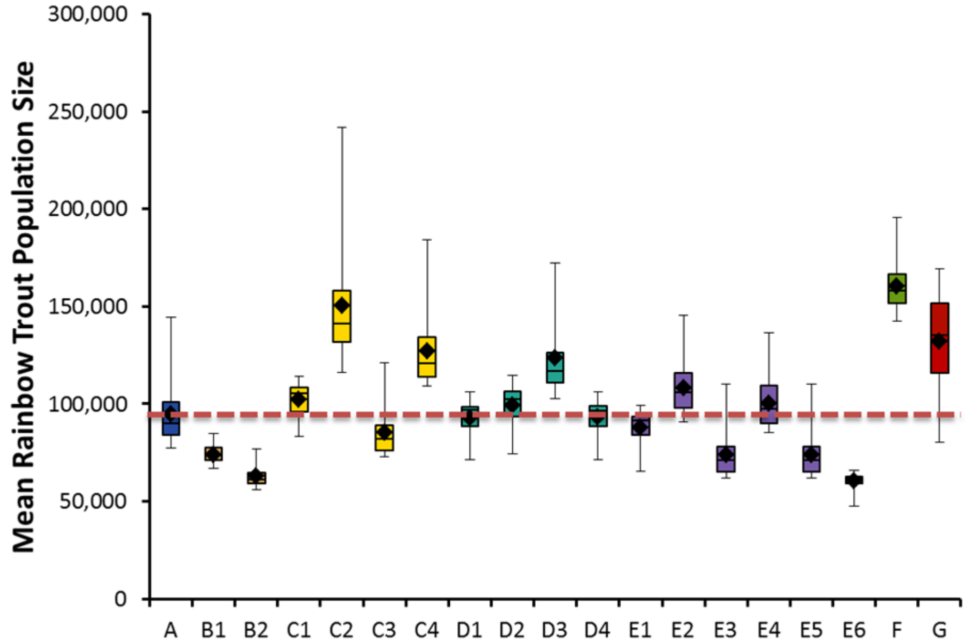

FIGURE F-10 Modeled Average Population Size of Age-1 and Older Rainbow Trout in the Glen Canyon Reach during the 20-year LTEMP Period under LTEMP Alternatives and Long-Term Strategies (The graph shows the mean, median, 75th percentile, 25th percentile, minimum, and maximum values for 21 hydrology scenarios and three sediment scenarios. Means were calculated as the average for all years within each of the 21 hydrology runs. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum; horizontal dashed line identifies mean value for Alternative A.)

of years with HFEs and the steady pattern of flows that would be maintained throughout the year without monthly differences in flow (other than those needed to adjust operations in response to changes in forecast and other operating requirements such as equalization); even at the highest evaluated levels of effectiveness for TMFs (50% reduction in age-0 trout), average annual recruitment would be expected to be quite high under Alternative G.

The overall modeled average rainbow trout abundance in the Glen Canyon reach was lowest under long-term strategies B1, B2, E3, E5, and E6. These long-term strategies generally would not allow spring HFEs (e.g., E3, E5, E6) or would be expected to have considerably fewer HFEs during the LTEMP period (e.g., B1, B2) than other long-term strategies, would maintain levels of fluctuations in flow similar to or greater than Alternative A, and (with the exception of long-term strategies E3 and E5) would implement TMFs. Thus, average annual recruitment levels would be expected to be lowest under these alternatives.

Modeled levels of trout abundance were intermediate and similar to Alternative A under long-term strategies C1, C3, D1, D2, D4, E1, E2, and E4. These long-term strategies generally included implementation of combinations of flow actions that would be expected to result in intermediate levels of trout recruitment (e.g., no spring HFEs in all or a portion of the LTEMP period together with higher levels of fluctuation) or included TMFs that would function to control recruitment in years with high levels of trout production (e.g., years with HFEs).

Abundance of Rainbow Trout >16 in. Total Length

The modeled abundance of large rainbow trout in the Glen Canyon reach (i.e., trout that would be larger than 16 in. total length) under LTEMP alternatives are summarized in Figure F-11. Among all the long-term strategies evaluated, the modeled abundance of these larger trout during the simulations of 20-year LTEMP periods ranged from 480 to 1,039 individuals (Figure F-11). Overall modeled means (i.e., mean number of large trout for all simulations) for the various long-term strategies ranged from 592 large fish under Alternative F to 956 large fish under long-term strategy E6 (Table F-8; Figure F-11). Compared to Alternative A, the model suggested that long-term strategies C2, C4, D3, F, and G would have fewer large trout; long-term strategies D1, D4, E1, and E4 would have similar numbers of large

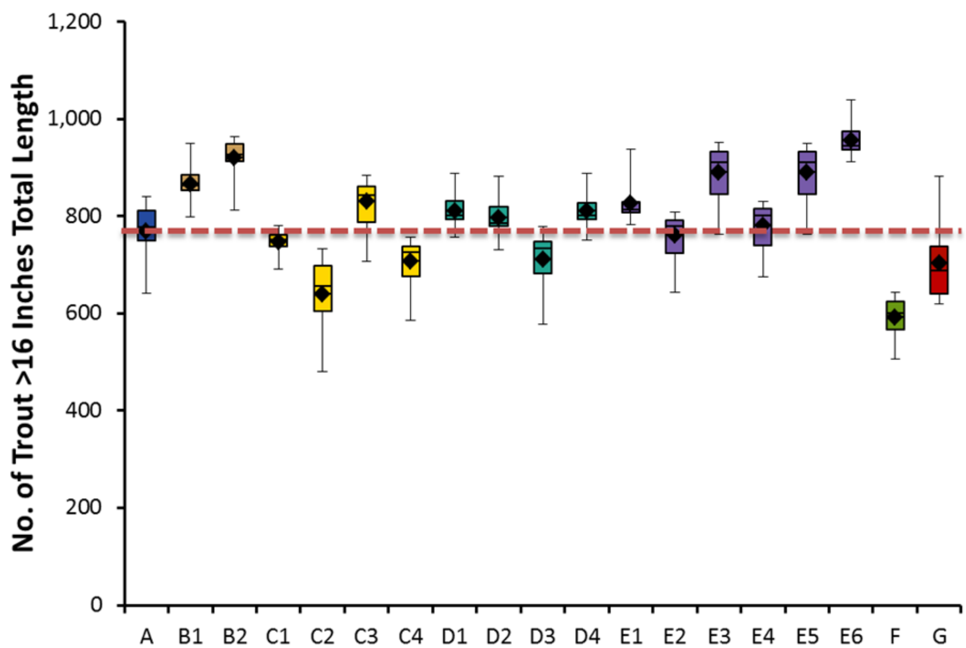

FIGURE F-11 Modeled Mean Annual Number of Rainbow Trout in the Glen Canyon Reach Exceeding 16 in. Total Length during the 20-year LTEMP Period under the LTEMP Alternatives and Long-Term Strategies (The graph shows the mean, median, 75th percentile, 25th percentile, minimum, and maximum values for 21 hydrology scenarios and three sediment scenarios. Means were calculated as the average for all years within each of the 21 hydrology runs. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum; horizontal dashed line identifies mean value for Alternative A.)

trout; and the remaining long-term strategies would have greater numbers of large trout (Figure F-11). It is generally expected that the average size of rainbow trout in the population would be inversely proportional to the average population size because of the effects of trout density on growth rates due to competition for food and other resources, and this was supported when comparing the modeled results for average number of large trout to the average number of trout in the Glen Canyon reach (Figure F-12). Because of their effect on lowering recruitment levels and population size, long-term strategies (such as long-term strategies B2 and E6) that have fewer HFEs, higher daily fluctuations, and that implement TMFs are expected to have a greater number of large trout. Table 4.1-1 identifies the experimental elements included in the various long-term strategies, and Appendix E of the DEIS describes the number and duration of HFEs that would be expected under the various long-term strategies.

Trout Catch Rates

The modeled angler catch rates for rainbow trout in the Glen Canyon reach under the LTEMP alternatives and long-term strategies are shown in Figure F-13. Modeled average catch rates during the simulations of 20-year LTEMP periods ranged from approximately 1.1 fish/hr to

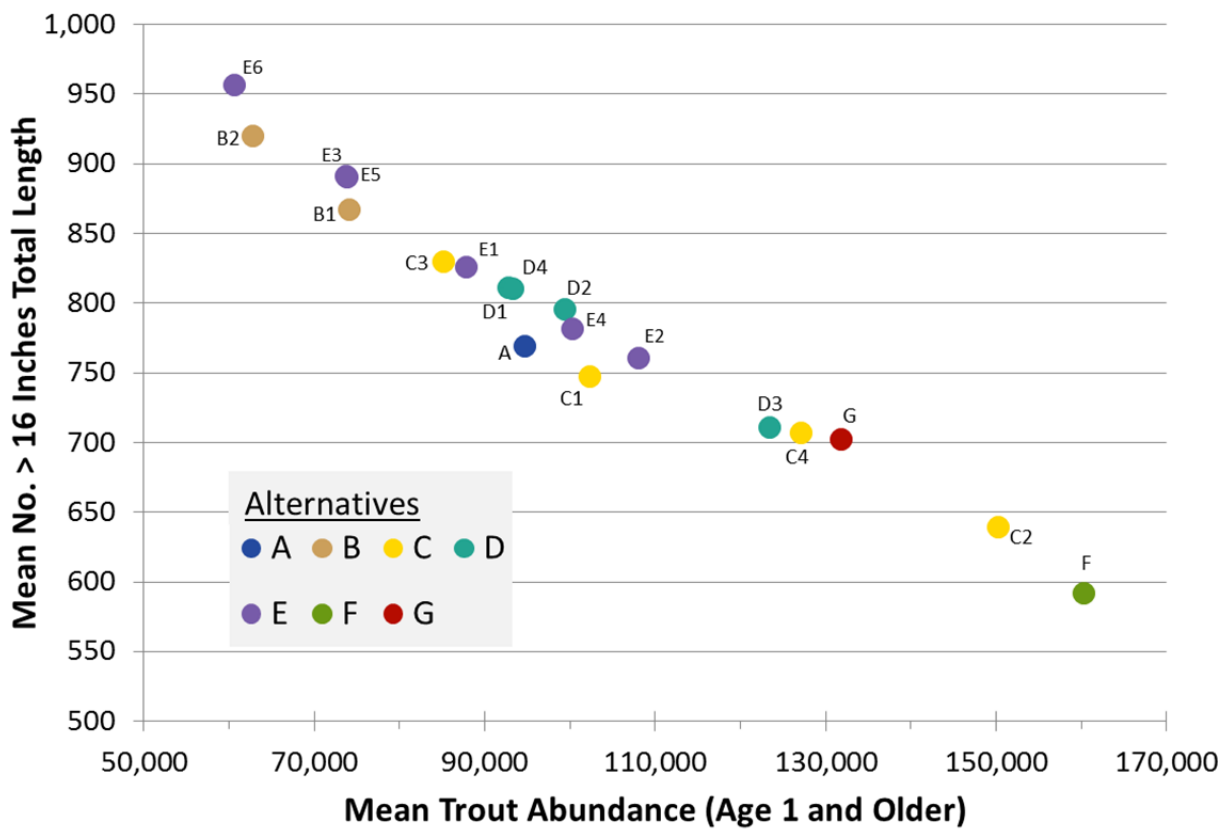

FIGURE F-12 Relationship between Modeled Mean Rainbow Trout Abundance in the Glen Canyon Reach and the Mean Number of Rainbow Trout Exceeding 16 in. Total Length during the 20-year LTEMP Period under the LTEMP Alternatives and Long-Term Strategies

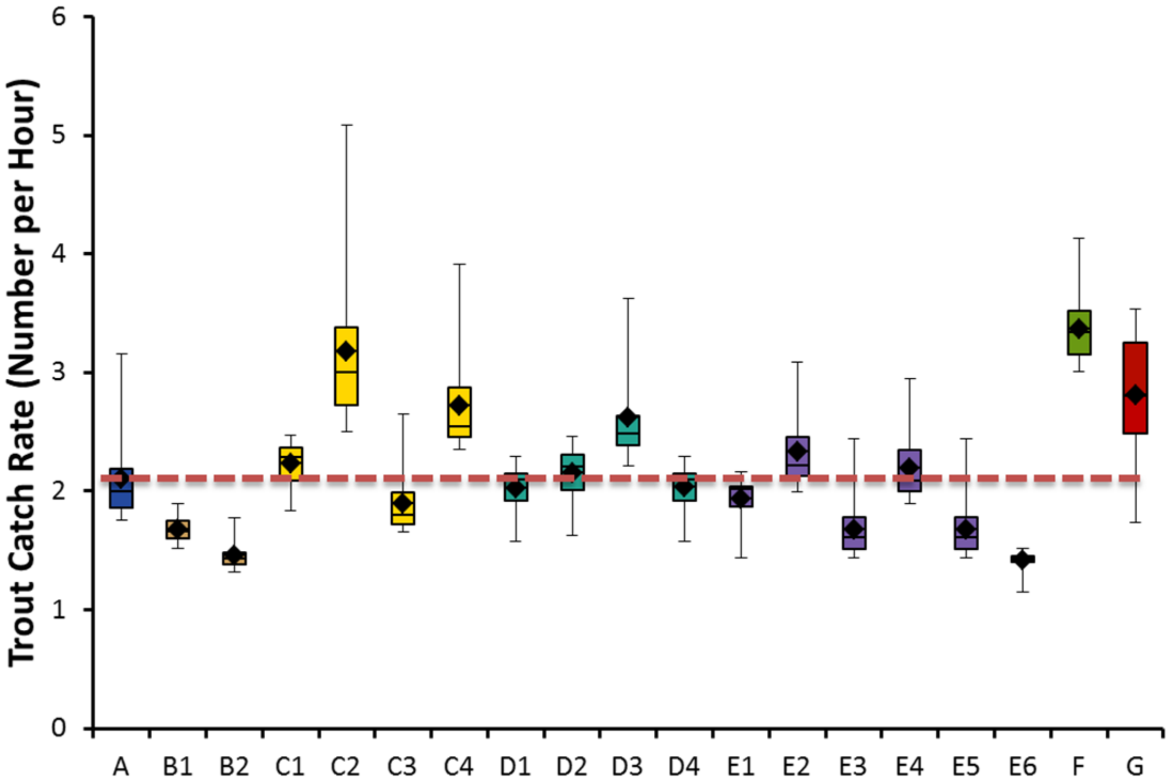

FIGURE F-13 Modeled Mean Annual Angler Catch Rate for Rainbow Trout in the Glen Canyon Reach during the 20-year LTEMP Period under the LTEMP Alternatives and Long-Term Strategies (The graph shows the mean, median, 75th percentile, 25th percentile, minimum, and maximum values for 21 hydrology scenarios and three sediment scenarios. Means were calculated as the average for all years within each of the 21 hydrology runs. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum; horizontal dashed line identifies mean value for Alternative A.)

5.1 fish/hr (Figure F-13).Modeled mean catch rates (i.e., mean catch rates for all simulations) ranged from 1.4 fish/hr under long-term strategy E6 to 3.4 fish/hr under long-term strategy F (Table F-8; Figure F-13). Compared to Alternative A, the model indicated that long-term strategies B1, B2, C3, E1, E3, E5, and E6 would have lower catch rates; long-term strategies C1, D1, D2, D4, and E4 would have similar catch rates; and long-term strategies C2, C4, D3, E2, F, and G would have higher catch rates (Figure F-13). Although the modeled vulnerability of individual trout to angling varies depending on the age of the trout, modeled average angler catch rates are highly correlated with average population levels of the long-term strategies, as shown in Figure F-14.

For this reason, the same combinations of experimental elements that drive recruitment levels and affect rainbow trout abundance would be expected to drive angler catch rates (see "Recruitment" in Section F.3.1.1 and "Rainbow Trout Population Estimates" in Section F.3.2.1). Thus, long-term strategies that result in more frequent HFEs (especially spring HFEs) have steadier flows and do not include TMFs (e.g., Alternatives F and G and long-term strategies C2

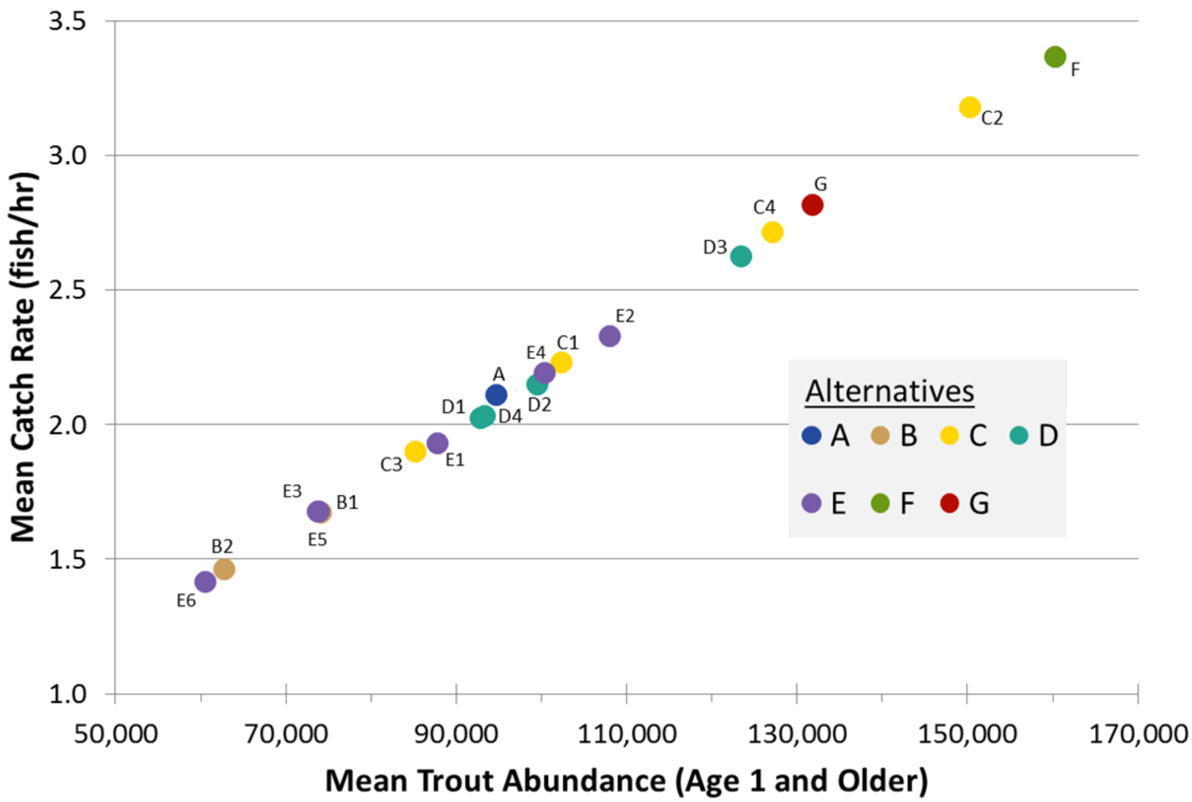

FIGURE F-14 Relationship between Modeled Mean Rainbow Trout Abundance in the Glen Canyon Reach and Mean Angler Catch Rates during the 20-year LTEMP Period under the LTEMP Alternatives and Long-Term Strategies

and D3) would be expected to have higher trout numbers and would lead to greater angler catch rates for rainbow trout, while long-term strategies that have fewer HFEs, more variable flows, and include TMFs (e.g., long-term strategies B1, B2, and E6) would be expected to have lower trout abundance and lower mean angler catch rates. Table 4.1-1 identifies the experimental elements included in the various long-term strategies, and Appendix E of the DEIS describes the number and duration of HFEs for each.

Trout Emigration

The modeled number of trout emigrating (i.e., number of out-migrants) from the Glen Canyon reach into the Marble Canyon reach of the Colorado River under the LTEMP alternatives and long-term strategies are summarized in Figure F-15. Modeled annual number of out-migrants ranged from approximately 18,200 fish/year to 114,900 fish/year (Figure F-15). Modeled mean annual number of out-migrants (i.e., mean number of out-migrants for all simulations) ranged from 22,415 fish/year under long-term strategy E6 to 71,869 fish/year under Alternative F (Table F-8; Figure F-15). Compared to Alternative A, the model indicated that long-term strategies B1, B2, E3, E5, and E6 would have lower numbers of out-migrants; long-term strategies C3 and E1 would have similar numbers of out-migrants; and long-term strategies

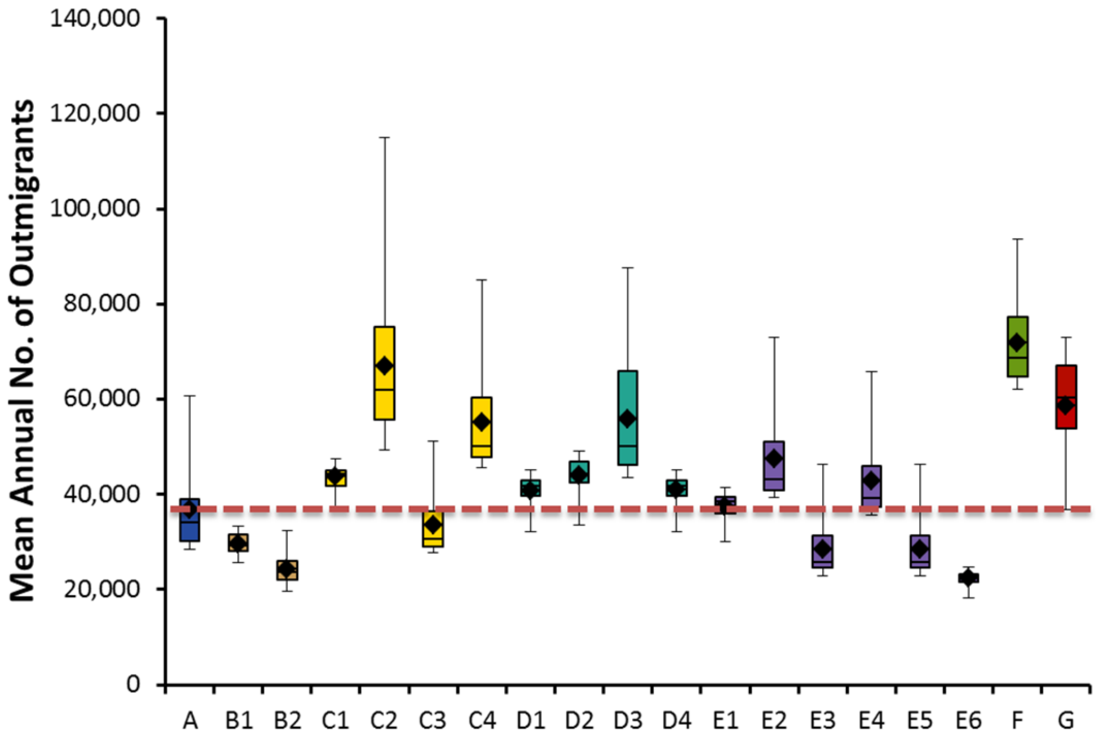

FIGURE F-15 Modeled Annual Average Number of Rainbow Trout Emigrating into the Marble Canyon Reach from the Glen Canyon Reach during the 20-year LTEMP Period under the LTEMP Alternatives and Long-Term Strategies (The graph shows the mean, median, 75th percentile, 25th percentile, minimum, and maximum values for 21 hydrology scenarios and three sediment scenarios. Means were calculated as the average for all years within each of the 21 hydrology runs. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum; horizontal dashed line identifies mean value for Alternative A.)

C1, C2, C4, D1, D2, D3, D4, E2, E4, F, and G would have higher numbers of out-migrants (Figure F-13).

As described in Section F.3.1.1, the annual number of trout emigrating from Glen Canyon into Marble Canyon was calculated as a function of the level of trout recruitment during the previous year. Thus, long-term strategies that result in more HFEs (especially spring HFEs), less variability in flows, and do not include TMFs (e.g., Alternatives F and G and long-term strategies C2, C4, D3, and E2) had higher modeled levels of trout emigration than long-term strategies with fewer HFEs, more variable flow regimes, and included TMFs (e.g., long-term strategies B1, B2, and E6). Table 4.1-1 identifies the experimental elements included in the various long-term, and Appendix E of the DEIS describes the number and duration of HFEs that would be expected under each.

Mechanical Removal of Trout in the Little Colorado River Reach

The modeled frequency of years in which mechanical removal of trout would be triggered in the Little Colorado River reach under the LTEMP alternatives and long-term strategies are summarized in Figure F-16. Mechanical removal is not included under long-term strategies C1, C2, E1, E2, E5, E6, and Alternative F. Among the remaining long-term strategies, the average number of years in which mechanical removal was triggered ranged from approximately 0.1 under Alternative A to approximately 3.1 under Alternative G (Table F-8; Figure F-16). The average maximum number of years in which mechanical removal would be triggered is 6.3 out of 20 years under long-term strategy D3. In general, long-term strategies that result in more frequent HFEs (especially spring HFEs), have steadier flows, and do not include TMFs (e.g., Alternatives F and G and long-term strategies C2, C4 and D3) have higher levels of recruitment, increase the number of trout that move downstream to the Little Colorado River reach, and meet conditions in the model that trigger mechanical removal of trout with a greater frequency. Long-term strategies that result in fewer HFEs and more variable flow levels (e.g., long-term strategies B1, B2, and E6) have lower levels of trout recruitment on average; inclusion of TMFs acts to further decrease the potential for large recruitment events. As a consequence, these long-term strategies result in lower numbers of trout entering the Little Colorado River reach and fewer years when mechanical removal is triggered. Table 4.1-1 identifies the experimental elements included in the various long-term strategies, and Appendix E of the DEIS describes the number and duration of HFEs that would be expected under each.

F.3.2.2 Humpback Chub Performance Measures

The modeled minimum population sizes for humpback chub adults under the LTEMP alternatives and long-term strategies are summarized in Figure F-17. Modeled minimum adult population sizes ranged from 1,433 to 13,478 fish (refer to upper and lower whiskers in Figure F-17). Overall modeled means (i.e., mean minimum number of adult humpback chub for all simulations) ranged from 4,450 individuals under Alternative F to 5,708 individuals under long-term strategy E6 (Table F-8; refer to diamonds in Figure F-17). The lowest modeled minimum adult population size (1,433 fish) was observed under long-term strategy C2, and the highest modeled minimum adult population size was observed under long-term strategy E6, although the lowest minimum adult population values were relatively similar among all long-term strategies (refer to lower whiskers in Figure F-17). Compared to Alternative A, the model indicated that long-term strategy C2 and Alternative F would have somewhat lower mean minimum adult population sizes; long-term strategies C1, C4, D1, D2, D3, D4, E1, E2, E4 and Alternative G would have similar mean minimum adult population sizes; and long-term strategies B1, B2, C3, E3, E5, and E6 would have higher mean minimum adult population sizes (Figure F-17). These results indicate that although there are small differences among the long-term strategies with regard to the predicted minimum number of adult humpback chub in the Little Colorado River aggregation, all long-term strategies would likely maintain the population above at least 1,000 adults throughout the 20-year LTEMP period.

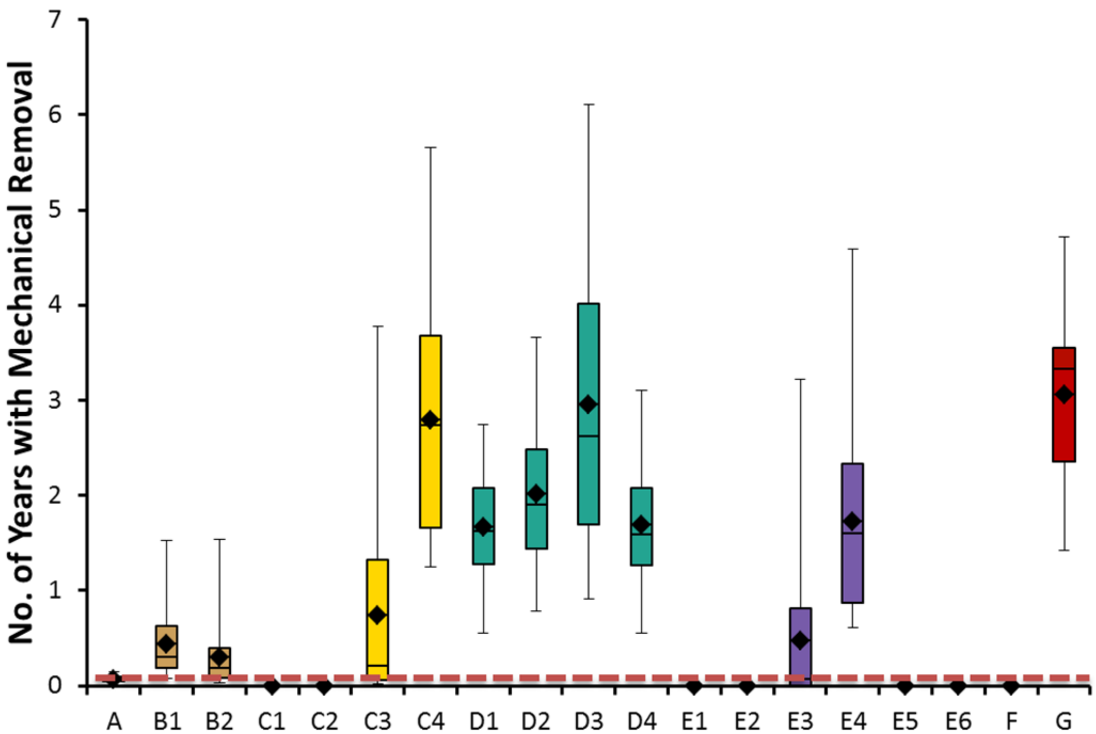

FIGURE F-16 Modeled Frequency of Triggered Mechanical Removal for Rainbow Trout in the Little Colorado River Reach during the 20-year LTEMP Period under the LTEMP Alternatives and Long-Term Strategies (The graph shows the mean, median, 75th percentile, 25th percentile, minimum, and maximum values for 21 hydrology scenarios and three sediment scenarios. Means were calculated as the average for all years within each of the 21 hydrology runs. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum; horizontal dashed line identifies mean value for Alternative A.)

In the humpback chub submodel, the factors that affect annual recruitment and survival of humpback chub are mainstem water temperatures and the number of trout in the Little Colorado River reach (Section F.3.1.3). Because there is little variation among the long-term strategies in modeled mainstem water temperatures at the confluence with the Little Colorado River, the differences in modeled numbers of adult humpback chub among the long-term strategies were primarily affected by the estimated abundance of trout in the Little Colorado River reach where survival of age-0 and juvenile humpback chub and subsequent recruitment of adult humpback chub could be affected by increased competition and predation (e.g., Yard et al. 2011). Because the modeled abundance of trout in the Little Colorado River reach is driven by modeled emigration of rainbow trout from the Glen Canyon reach, there is a strong relationship between the average adult humpback chub population size and the average number of trout emigrating from the Glen Canyon reach for the various long-term strategies (Figure F-18). Refer to the section above entitled “Trout Emigration” for information about the experimental elements of long-term strategies that affect the levels of trout emigration. Although the model predicts that

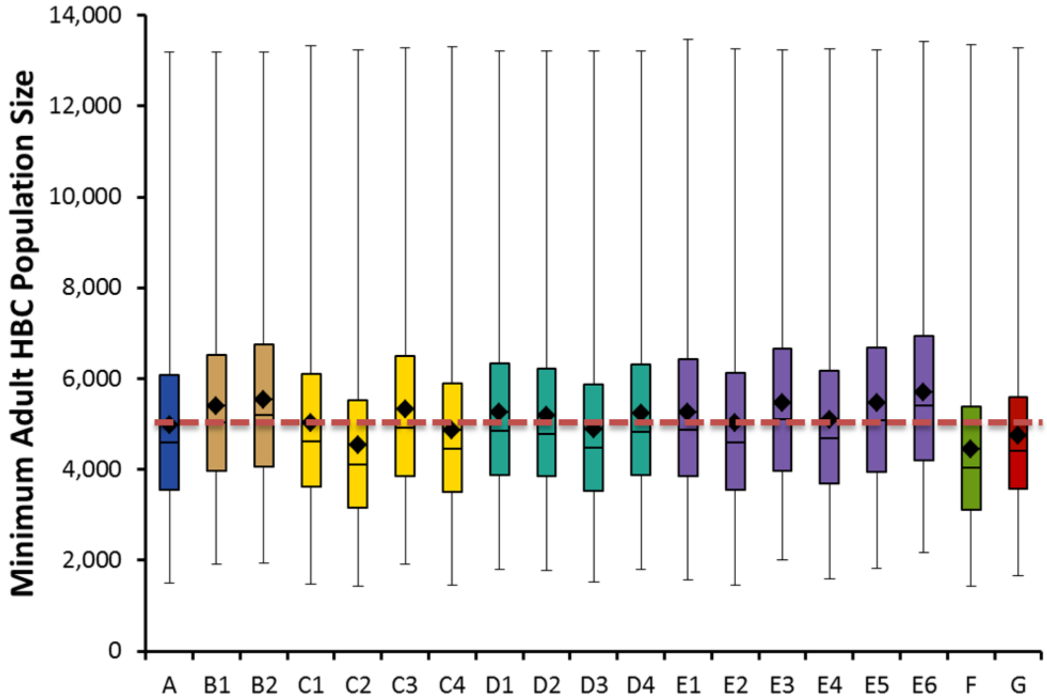

FIGURE F-17 Modeled Minimum Population Size for Humpback Chub (HBC) during the 20-year LTEMP Period under the LTEMP Alternatives and Long-Term Strategies (The graph shows the mean, median, 75th percentile, 25th percentile, minimum, and maximum values for 21 hydrology scenarios and three sediment scenarios. Means were calculated as the average for all years within each of the 21 hydrology runs. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum annual value for all simulations; upper whisker = maximum annual value for all simulations; horizontal dashed line identifies mean value for Alternative A.)

the number of trout at the confluence with the Little Colorado River is related to trout recruitment in the Glen Canyon reach, the actual relationship is unclear and still under investigation.

F.4 MODELING THE EFFECTS OF LTEMP ALTERNATIVES ON TEMPERATURE SUITABILITY

This section describes the modeling approach used to evaluate the effects of LTEMP EIS alternatives on temperature suitability for fishes and invertebrate parasites in the mainstem Colorado River downstream of Glen Canyon Dam. The goal of the temperature suitability modeling was to evaluate the potential for each of the alternatives to result in temperature conditions that would promote maintenance and/or establishment of various fish and invertebrate

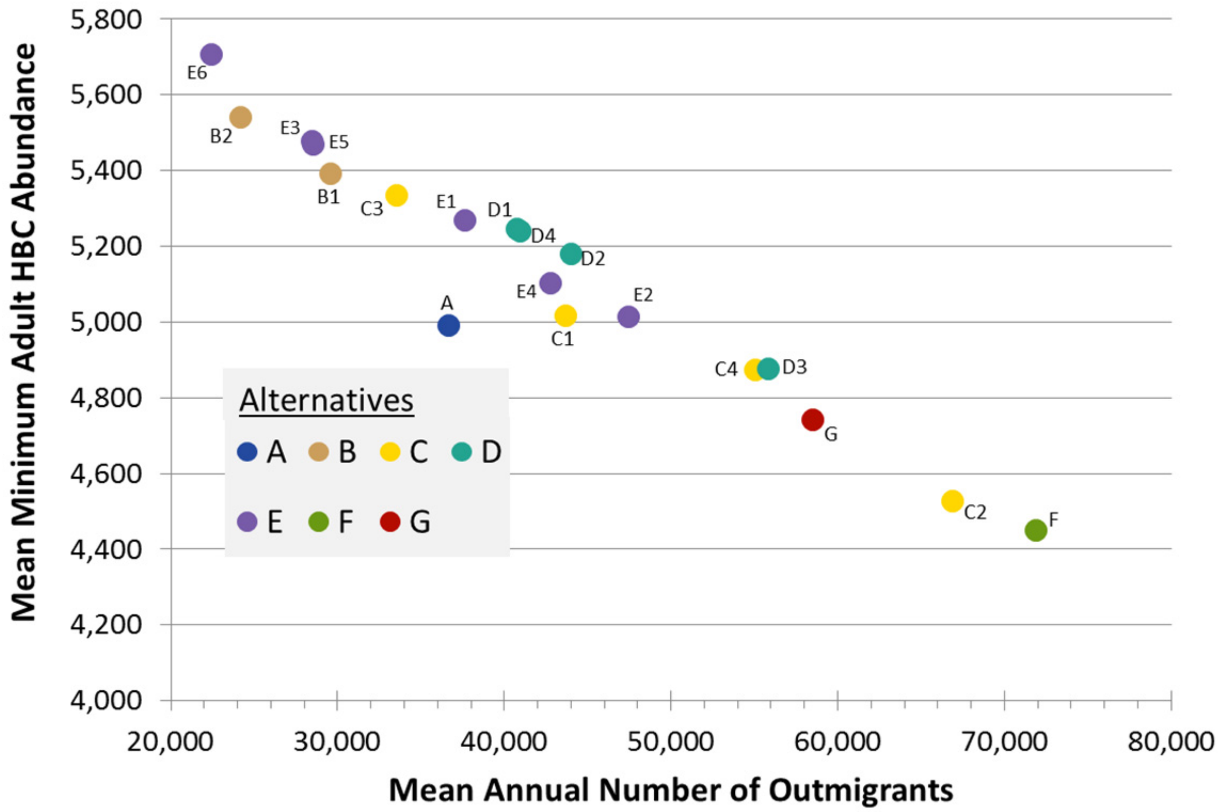

FIGURE F-18 Relationship between Modeled Mean Numbers of Rainbow Trout Out-migrants from the Glen Canyon Reach and the Modeled Mean Minimum Abundance of Adult Humpback Chub during the 20-year LTEMP Period under the LTEMP Alternatives and Long-Term Strategies

species of management concern. In particular, the temperature suitability modeling is intended to evaluate effects of alternatives on temperature suitability for four species groups:

1. Temperature suitability for establishment and maintenance of self-sustaining aggregations of humpback chub at various river locations in the Colorado River downstream of Glen Canyon Dam;

2. Temperature suitability for establishment and maintenance of self-sustaining populations of native warmwater fish other than humpback chub at various locations in the Colorado River downstream of Glen Canyon Dam;

3. Temperature suitability for establishment and maintenance of self-sustaining populations of nonnative fish species at various locations in the Colorado River downstream of Glen Canyon Dam; and

4. Temperature suitability for establishment and maintenance of self-sustaining populations of parasitic invertebrate species at various locations in the Colorado River downstream of Glen Canyon Dam.

The following sections describe the general modeling approach for evaluating temperature suitability, specific modeling considerations applied in order to implement the modeling approach for each of the species groups to be evaluated, the input data needs and sources for each of the ecological components, and the approach for statistically evaluating the output of the models in order to compare the effects of the various operational alternatives on temperature suitability for each species group.

F.4.1 Model Overview

In general, the temperature suitability modeling considers how well mainstem water temperatures at selected locations downstream of Glen Canyon Dam would meet the temperature requirements for three life history components—spawning, egg incubation, and growth—for each species group evaluated. To accomplish this, monthly water temperature values in a multi-year time series were compared to temperature suitability profiles for life history components of each species group considered. The seasonal timing or period of the year during which the temperature needs for each life history component must be met is taken into account by the model. Possible values for temperature suitability can theoretically range from 0 (completely unsuitable for one or more life history component) to 1 (magnitude and timing of temperatures would be optimal for all life history components). However, since optimal conditions for all life history components cannot be simultaneously met in many cases (due to different optimal temperatures during overlapping time frames, the maximum attainable value for a given species would generally be less than one.

The temperature suitability modeling evaluates the potential for all life history components to be met in the mainstem river, even though some species are known to sometimes use tributaries to accomplish particular needs. Thus, the model can predict relatively low temperature suitability for some areas even though species populations appear to be abundant and self-sustaining. In addition, modeled water temperatures used as inputs do not consider the potential for warming near tributary mouths, backwater habitats, or in shallow nearshore areas. Thus, the results of temperature suitability modeling are used to compare relative effects of alternatives on species-specific temperature needs in the mainstem Colorado River, rather than as an exact predictor of the potential for the presence or absence of fish or parasite species at particular locations.

For fish species, the model considers the suitability of each day’s water temperature for three life history components (spawning, egg incubation, and growth). The model bases the potential for self-sustaining populations of fish species being successful on the combined temperature suitability scores for spawning, incubation, and growth, and it is assumed that some level of both mainstem spawning and egg incubation would be required to support self-sustaining populations of fish species. The annual potential for successful spawning and egg incubation is assumed to be related to the suitability of the annual temperature regimes for spawning and egg incubation during the spawning and egg incubation periods. It was assumed that the potential for successful rearing and survival of fish species within the mainstem at each evaluation location was related to the suitability of temperatures throughout the year for growth. The suitability of various temperatures for meeting spawning, egg incubation, and growth needs of fish was calculated using triangular probability functions[3] based upon reported suitable ranges and optimal temperatures for each life history aspect of each species (Valdez and Speas 2007).

For parasite species, the model bases the potential for unacceptable parasite conditions on the temperature suitability scores for host activity and infestation. It is assumed that both elevated host activity and infestation rates would be needed to result in unacceptable infestations of the parasite species and the annual potential for unacceptable infestations is assumed to be related to the suitability of the temperature regimes for host activity and infestation throughout the year. The suitability of various temperatures for host activity and infestation needs of a group of four parasite species was calculated using triangular probability functions based on the reported range of suitable temperatures and the reported optimal temperature for each species (Valdez and Speas 2007). The model calculates daily temperature suitability scores for the life history components based on the triangular suitability relationships and the seasonal time periods during which the temperature needs for each life history component must be met.

Annual temperature suitability for each life history component is calculated as the mean of the daily suitability values that fall within the specified seasonal time period during a given water year. The overall annual temperature suitability for each species is calculated as the geometric mean of the annual temperature suitability scores for the applicable species-specific life history components. Temperature suitability over a 20-year period is based on the mean of the annual temperature suitability values. Evaluations were conducted for each river location to be assessed or using the overall annual means for combinations of downstream locations. The mean of the annual suitability scores for multiple fish or parasite species was used as an indication of the overall suitability of each year's temperature regime for groups of native fish, nonnative fish, or parasite species.

The LTEMP temperature suitability model requires inputs pertaining to daily water temperatures for each of the downstream locations to be assessed and requires identification of temperature requirements for the life history aspects of each species to be evaluated. Species-specific temperature requirement information includes the minimum, optimal, and maximum suitable temperatures for important life history components and information describing the appropriate months of the year during which conditions for each life history component should be met. Table F-9 summarizes the input data needs and the anticipated sources of the input values. The model is formulated to consider daily water temperatures for multi-year periods. The daily water temperature input values were derived from external modeling (i.e., not calculated within the LTEMP temperature suitability model) following formulas developed by Wright et al. (2009) to predict mean monthly water temperatures at various locations downstream of Glen

[3] With the triangular functions used, the temperature suitability value rises linearly from 0 at the minimum suitable temperature to 1 at the optimum temperature, then falls linearly from 1 at the optimum to 0 at the maximum suitable temperature). Each of these functions was based on species-specific temperature requirements as reported by Valdez and Speas (2007). See Figure F-19 for example functions.

TABLE F-9 Description of Input Parameters for the LTEMP Temperature Suitability Model

Input Parameter	Description of Input Data	Comments
$TW_{x,\,y}$	Mean daily water temperature (°C) for a specific day (*x*) in a given year (*y*)	Provided by water temperature modeling. Although daily water temperatures are used as inputs into the model, modeled mean monthly water temperatures were used to provide the mean daily temperatures to be used within the months for each year. The model is formulated to accommodate multi-year traces of daily temperature data. A water temperature time series covering the same time period was developed for each downstream location.
$T_{Min\ (s,l)}$	The minimum suitable temperature (°C) to meet a given life history need (*l*) for a given species (*s*)	Values obtained from Valdez and Speas (2007).
$T_{Max\ (s,l)}$	The maximum suitable temperature (°C) to meet a given life history need (*l*) for a given species (*s*)	Values obtained from Valdez and Speas (2007).
$T_{Opt\ (s,l)}$	The optimum suitable temperature (°C) to meet a given life history need (*l*) for a given species (*s*)	Values obtained from Valdez and Speas (2007).
$MonthStart_{(s,l)}$	The beginning month of the water year during which a given life history need (*l*) for a given species (*s*) should be met	Used to identify the beginning of the appropriate time period for meeting each species–life history component combination.
$MonthEnd_{(s,l)}$	The ending month of the water year during which a given life history need (*l*) for a given species (*s*) should be met	Used to identify the end of the appropriate time period for meeting each species–life history component combination.

Canyon Dam based on assumed meteorological conditions, the expected magnitude of water releases, and the temperature of the water being released from Lake Powell for each of the LTEMP alternatives. The temperature suitability for each alternative/long-term strategy was evaluated using a total of 63, 20-year temperature input scenarios generated from conditions expected during operations for a range of hydrology–sediment trace combinations. The temperature suitability model was implemented using R (R Core Team 2013; see http://www.r-project.org/about.html).

The following sections provide specific information regarding implementations and results of the temperature suitability modeling approach to evaluate suitability for (1) self-sustaining aggregations of humpback chub; (2) self-sustaining populations of native warmwater fish species other than humpback chub; (3) self-sustaining populations of coldwater and warmwater nonnative fish species; and (4) establishment and maintenance of invasive parasitic invertebrate species.

F.4.2 Humpback Chub Aggregations

The temperature suitability model evaluates how well alternatives would provide mainstem water temperatures suitable for spawning, egg incubation, and growth of humpback chub at reported aggregation locations. The model based the potential for a self-sustaining aggregation of humpback chub becoming successfully established at each location on the combined potential for successful spawning, successful incubation, and successful growth of humpback chub. The time series of water temperatures was based upon estimated water temperatures for eight mainstem Colorado River locations (Table F-10) where humpback chub aggregations have been reported to occur. As described in Section F.4.1, the water temperatures used as inputs for these locations were modeled using a water temperature model developed by Wright et al. (2009).

It was assumed that mainstem spawning would be required to support self-sustaining aggregations at all locations except for the aggregation at the confluence of the mainstem and the Little Colorado River (RM 61), where successful tributary spawning is known to occur. Thus, except for the Little Colorado River aggregation, the annual potential for successful spawning is assumed to be related to the suitability of temperature regimes in the mainstem Colorado River for spawning. The potential for successful spawning at various temperatures was calculated using a triangular probability function based upon the reported range of suitable spawning temperatures (16–22°C) (61–72°F) and the reported optimal spawning temperature (18°C) (64°F) for humpback chub (Valdez and Speas 2007). The calculated suitability of various water temperatures for successful humpback chub spawning is shown in Figure F-19.

April, May, and June were identified as encompassing the possible spawning period for humpback chub aggregations (Figure F-20), based on observations of fish in spawning condition reported by Valdez and Ryel (1995) for aggregations and by Gorman and Stone (1999) for spawning in the Little Colorado River. The annual suitability values for spawning were set to a value of 1 for the Little Colorado River aggregation, since water temperature in the Little

TABLE F-10 Humpback Chub Aggregation Locations

Aggregation Location	River Mile (RM)[a]
30-mile	RM 30
Little Colorado River confluence	RM 61
Bright Angel Creek	RM 88
Shinumo Creek	RM 108
Stephen Aisle	RM 119
Middle Granite Gorge	RM 125
Havasu Creek	RM 157
Pumpkin Spring	RM 213

[a] River mile distances are calculated as the distance downstream from the Lees Ferry gage.

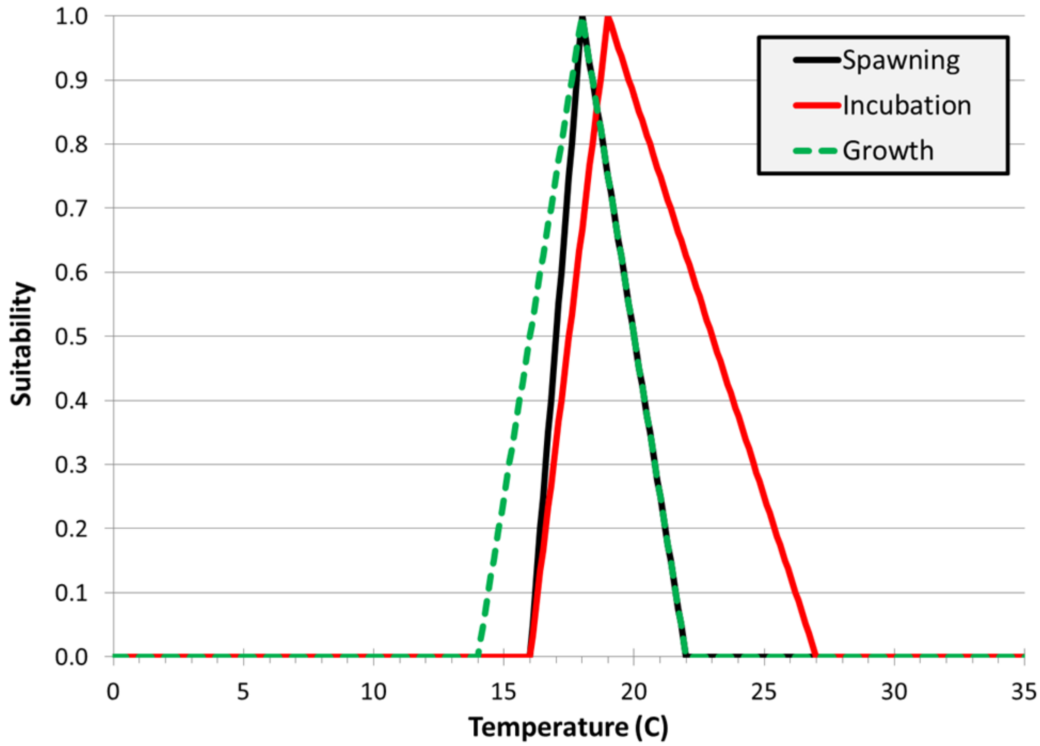

FIGURE F-19 Suitability for Spawning, Egg Incubation, and Growth of Humpback Chub as a Function of Water Temperature (based on minimum, maximum, and optimum temperature values presented in Valdez and Speas 2007)

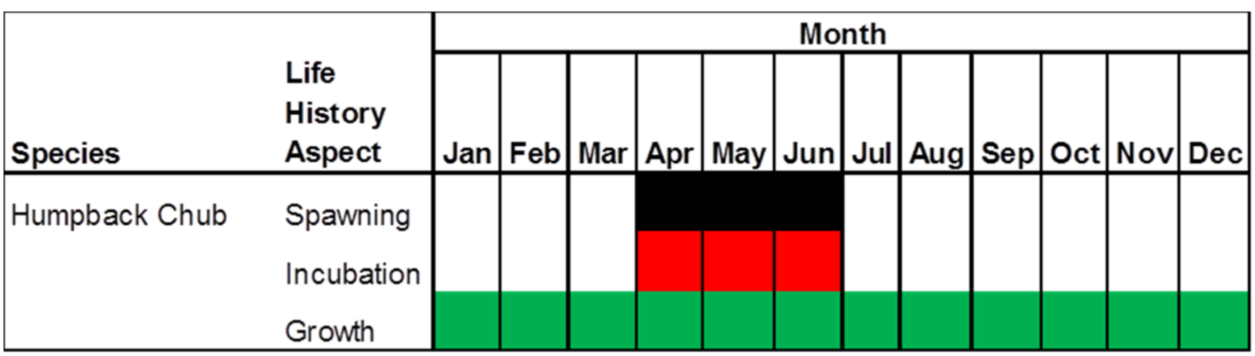

FIGURE F-20 Months for Which Annual Temperature Suitability for Specific Life History Aspects of Humpback Chub Were Calculated

Colorado River is known to support spawning needs for this aggregation. The potential for successful spawning during a given water year for each aggregation was calculated as the average of the estimated suitability scores during April through June (Figure F-20).

It was assumed that mainstem egg incubation would be required to support self-sustaining aggregations at all locations except for the aggregation at the confluence of the mainstem and the Little Colorado River (RM 61), where successful tributary spawning is known to occur. The suitability for incubation in the Little Colorado River (RM 61) aggregation was assumed to be 1. At other aggregation locations, the annual potential for successful egg incubation was assumed to be related to the suitability of mainstem temperature regimes for incubation during the spawning period, because incubation of humpback chub eggs may require as little as 3 days at optimal temperatures. Thus, it was assumed that the spawning period of April, May, and June also encompassed the egg incubation period for aggregations (Figure F-20). The suitability of various temperatures for egg incubation was calculated using a triangular probability function based upon the reported range of suitable egg incubation temperatures (16–27°C) (61–81°F) and the reported optimal egg incubation temperature (19°C) (66°F) for humpback chub (Valdez and Speas 2007;Figure F-19).

It was assumed that the potential for successful rearing of humpback chub within the mainstem at each aggregation location is related to the suitability of temperatures throughout the year for humpback chub growth. The suitability of various temperatures for growth of humpback chub was calculated using a triangular probability function based upon the reported range of suitable temperatures (16–22°C) (61–72°F) and the reported optimal temperature (18°C) (64°F) for growth (Valdez and Speas 2007; Figure F-19). The annual suitability of daily temperatures for growth was calculated as the mean of daily suitability values during the entire water year (Figure F-20).

The geometric mean of the annual temperature suitability values for spawning, egg incubation, and growth was used as an indicator of the annual potential for an aggregation to be successful (and self-sustaining) at a particular location. The arithmetic mean of the annual suitability scores for each of the eight aggregation locations was used as an indication of the overall relative suitability of each year's temperature regime for supporting humpback chub aggregations in the mainstem Colorado River downstream of Glen Canyon Dam.

F.4.2.1 Historic Temperature Suitability for Humpback Chub

Historic temperature suitability of mainstem water temperatures for humpback chub aggregations was examined using modeled water historic temperatures at the aggregation locations for a 23-year period from October 1, 1989, through September 30, 2012 (water years 1990–2012), as the temperature inputs (Figure F-21). The annual values of the modeled historic temperature suitability for the various aggregation locations are summarized in Figure F-22.

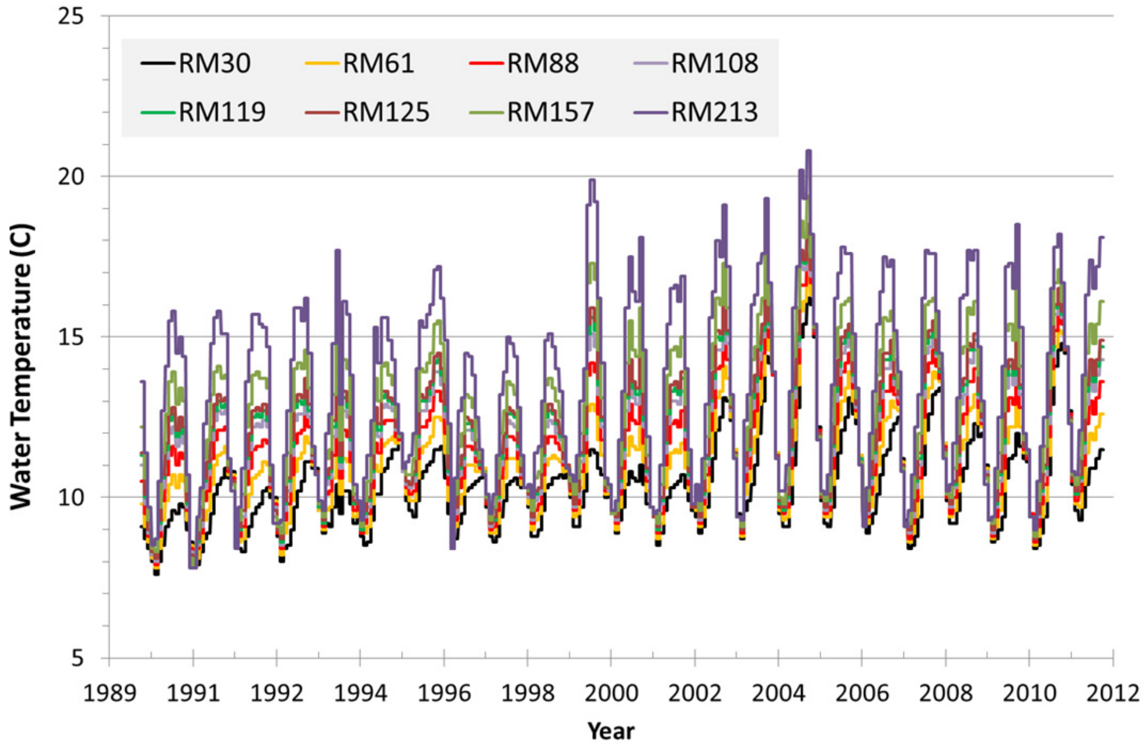

FIGURE F-21 Modeled Historic Water Temperatures in the Colorado River at Humpback Chub Aggregation Locations, Water Years 1990–2012 (Source: Williams 2013)

F.4.2.2 Results for LTEMP Alternatives

The temperature suitability for humpback chub at aggregation locations under the LTEMP alternatives and long-term strategies is summarized in Figure F-23. Modeled main channel water temperature suitability for humpback chub was relatively low and similar to Alternative A under all the long-term strategies for most aggregation locations. Modeled mean annual main channel temperature suitability for humpback chub at RM 61 (the Little Colorado River confluence) was slightly higher under Alternative F than under the other long-term strategies (Figure F-23), because the lower summer and fall flows of this alternative resulted in warmer water that would benefit growth during those seasons; note that the overall suitability score for RM 61 reflects temperature suitability for growth in the main channel, but optimal spawning and egg incubation temperatures in the Little Colorado River where the species spawns. Because the water warms as it travels downstream from the dam (for spring through fall months), temperature suitability improves with increasing distance. At RM 213, mean annual temperature suitability for humpback chub was similar to Alternative A under all long-term strategies except for C1, C2, C3, C4, and Alternative F. Compared to Alternative A, long-term strategies C1, C2, C3, and C4 were slightly lower, although differences were small (Figure-F-23). Modeled temperature suitability at RM 213 was lowest under Alternative F (Figure F-23), reflecting the higher, colder flows expected to occur under this alternative during spawning and egg incubation periods (April through June). Based on these results, the combined suitability of mainstem temperatures for spawning, egg incubation, and growth by humpback

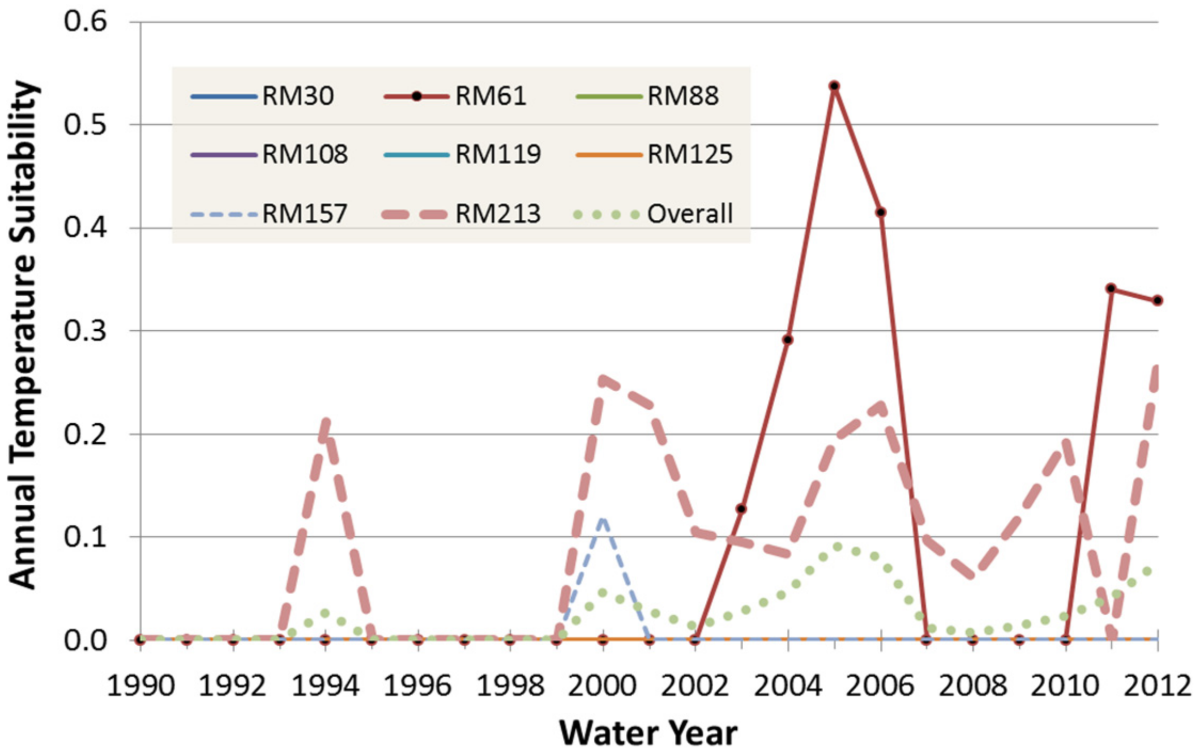

FIGURE F-22 Output from the Temperature Suitability Model for Humpback Chub Aggregation Locations Based on Modeled Water Temperatures for Water Years 1990–2012

chub in the downstream-most aggregation sites is anticipated to be negatively affected compared to current conditions under Alternative F; however, for the other long-term strategies, suitability would remain similar to the low historic levels, as represented by the suitability under Alternative A (the no-action alternative). It should be noted that, historically, there have been years where the magnitude and timing of mainstem water temperatures have likely coincided to allow spawning and egg incubation to occur in some of the downstream aggregation areas; however, the overall average suitability has likely been low (Figure F-22).

F.4.3 Other Native Fish

The temperature suitability model for native fish evaluates how well alternatives provide mainstem water temperatures suitable for spawning, egg incubation, and growth of four species of warmwater native fish other than humpback chub (speckled dace [*Rhinichthys osculus*], razorback sucker [*Xyrauchen texanus*], flannelmouth sucker [*Catostomus latipinnis*], and bluehead sucker [*C. discobolus*]). In order to account for changes in water temperatures as water released from Glen Canyon Dam travels downstream, evaluations of temperature suitability were conducted for five mainstem Colorado River locations (Table F-11). As described in Section F.4.1, the time series of water temperatures used as inputs for these locations are generated using a water temperature model developed by Wright et al. (2009).

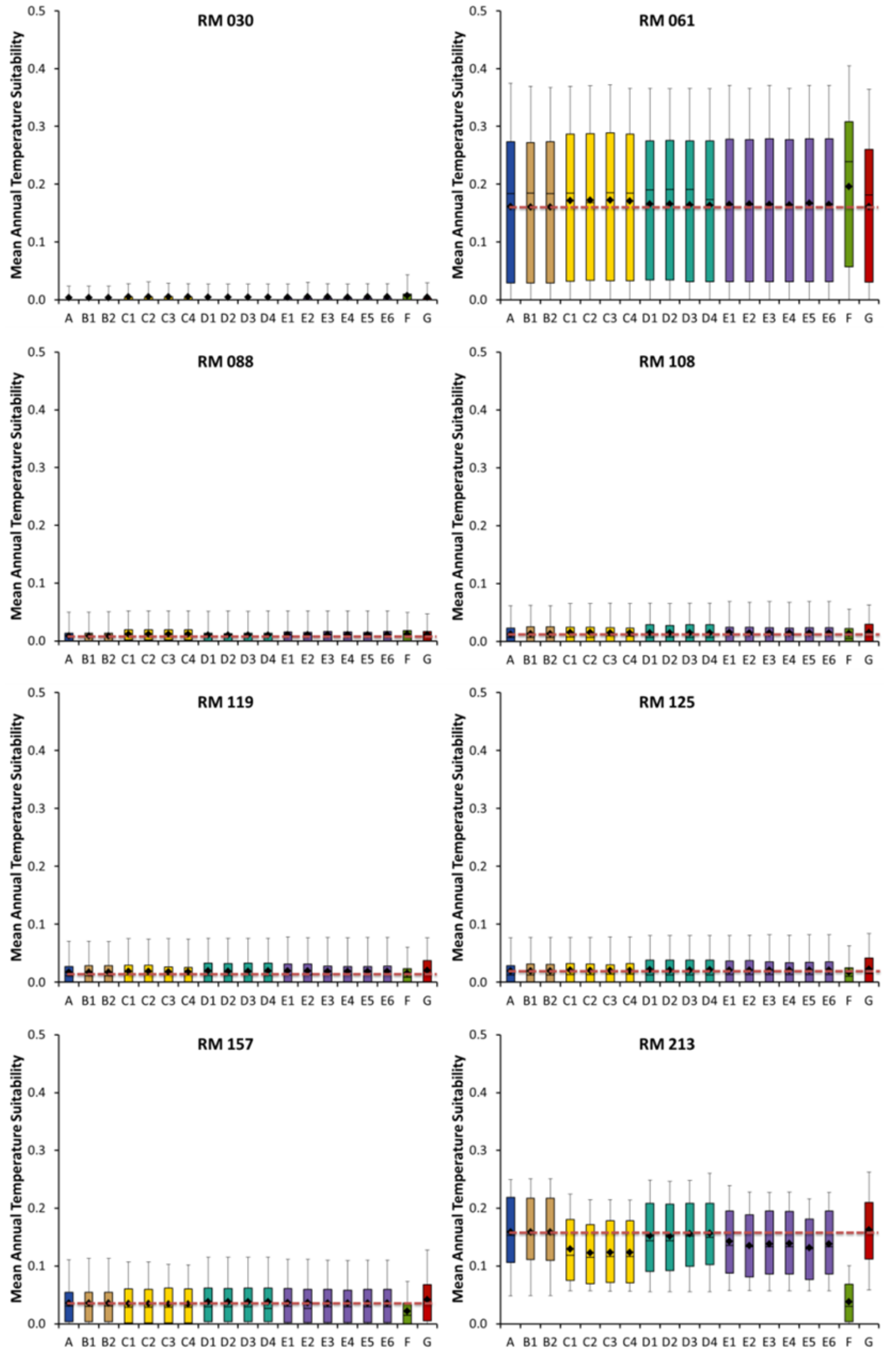

FIGURE F-23 Mainstem Temperature Suitability for Humpback Chub Aggregation Locations under LTEMP Alternatives and Long-Term Strategies (The graph shows the mean, median, 75th percentile, 25th percentile, minimum, and maximum values for 21 hydrology scenarios and three sediment scenarios. Means were calculated as the average for all years within each of the 21 hydrology runs. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum; horizontal dashed line identifies mean value for Alternative A.)

TABLE F-11 Locations Used for Temperature Suitability Modeling of Native Fish, Nonnative Fish, and Parasites

Aggregation Location	River Mile (RM)[a]
Glen Canyon Dam	RM –15
Paria River/Lees Ferry	RM 0
Little Colorado River confluence	RM 61
Havasu Creek	RM 157
Diamond Creek	RM 225

[a] River mile distances are calculated as the distance downstream from the Lees Ferry Gage. Glen Canyon Dam is indicated as being at RM –15, since it is located upstream of Lees Ferry.

The calculated suitability of various water temperatures for successful spawning, egg incubation, and growth of the four native species is depicted in Figure F-24. The months encompassing the spawning, egg incubation, and growth periods for each of the four native fish species are indicated in Figure F-25.These time periods were identified by reviewing the scientific literature pertaining to each of the species.

F.4.3.1 Historic Temperature Suitability for Native Fish

Historic temperature suitability of mainstem water temperatures for the four native fish species was examined using modeled water historic temperatures at five evaluation locations for a 23-year period from October 1, 1989, through September 30, 2012 (water years 1990–2012) as the temperature inputs (Figure F-26). Figure F-27 presents the annual temperature suitability scores for spawning, incubation, and growth of the four native fish species based upon the modeled historic temperatures for water years 1990–2012 at RM 225 (Diamond Creek). The annual temperature suitability scores for the five river locations and a combined overall score for all locations based on the modeled historic temperature suitability for the various assessment locations are presented in Figure F-28. The overall means of annual suitability scores at each river location for native fish over the 1990–2012 water years are presented in Figure F-29.

F.4.3.2 Results for LTEMP Alternatives

The temperature suitability for the four native fish at multiple downstream locations under the LTEMP alternatives and long-term strategies is summarized in Figure F-30. Modeled main channel water temperature suitability for native fish species was relatively low and similar to Alternative A under all long-term strategies at RM 61, reflecting the prevalence of coldwater releases from Glen Canyon Dam throughout the year and the limited effect that the long-term strategies would have on mainstem water temperature regimes at RM 61. Because the water

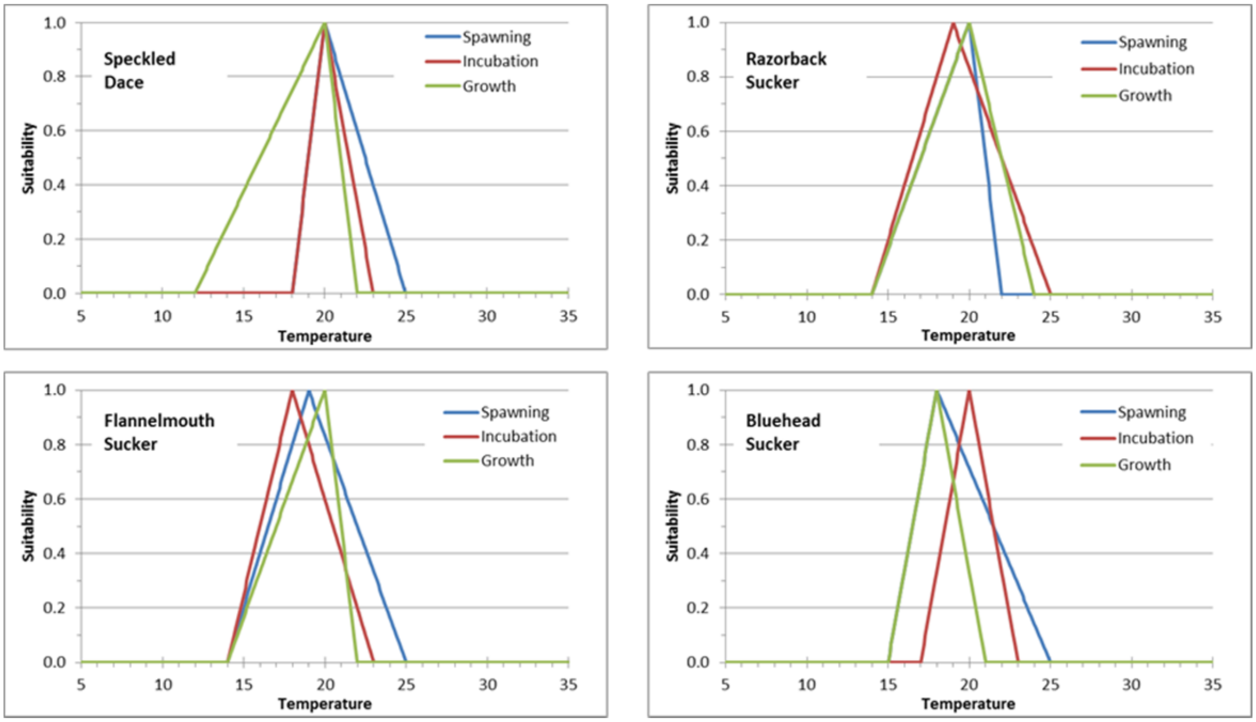

FIGURE F-24 Suitability of Water Temperatures (°C) for Spawning, Egg Incubation, and Growth of Native Fish Species (Source: Valdez and Speas 2007)

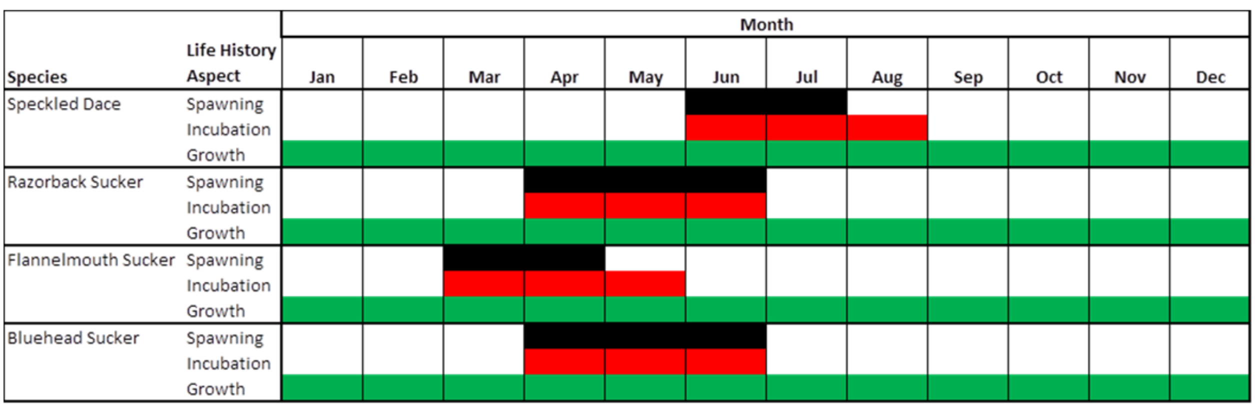

FIGURE F-25 Months for Which Temperature Suitability for Specific Life History Aspects Were Considered for Native Fish Species

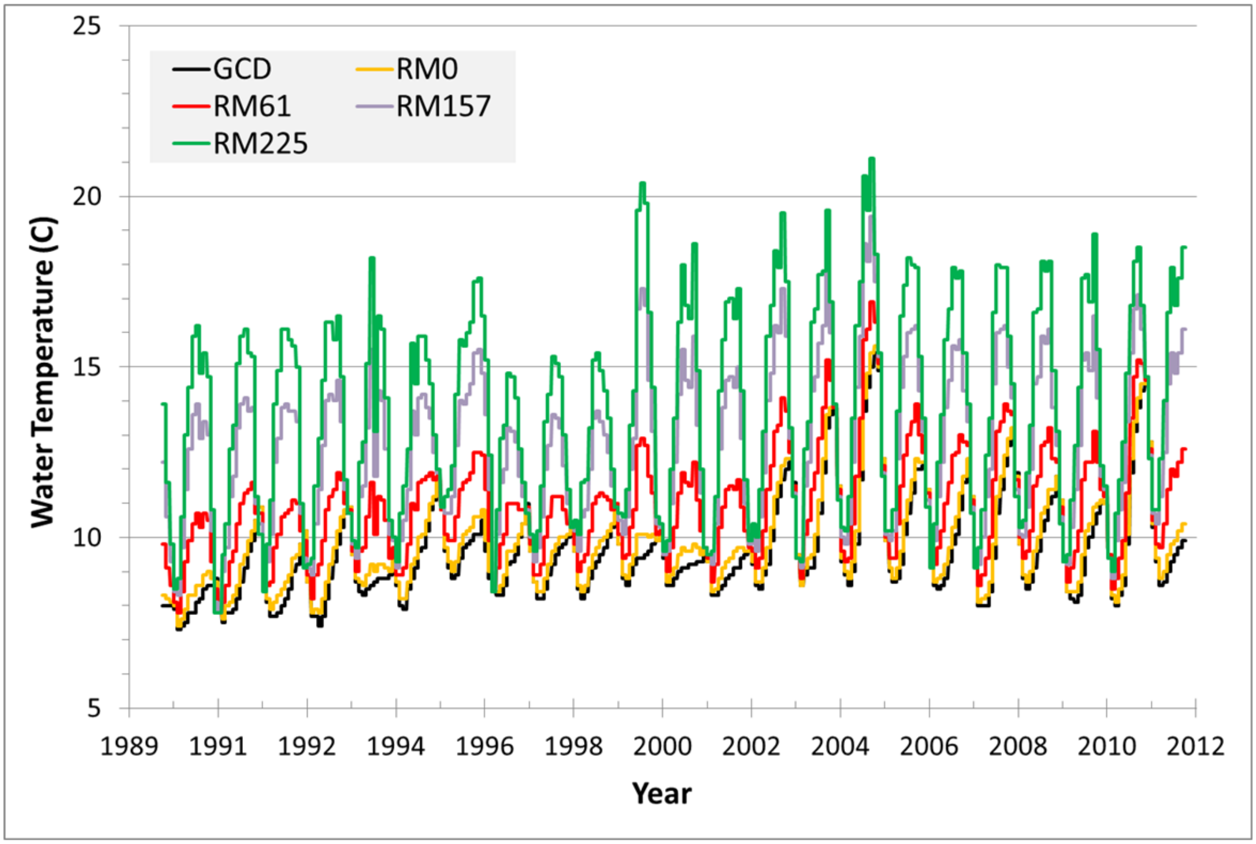

FIGURE F-26 Modeled Historic Water Temperatures in the Colorado River Downstream of Glen Canyon Dam, Water Years 1990–2012 (Source: Williams 2013)

warms as it travels downstream from the dam (for spring through fall months), temperature suitability improves with increasing downstream distance, and differences in suitability among the long-term strategies begin to appear. Whereas suitability for most long-term strategies remain similar to, or lower than, the modeled suitability under Alternative A at these downstream locations, temperature suitability for native fish improves somewhat under long-term strategies D1, D2, D3, and D4 (Figure F-30). It should be noted that there is little difference in temperature suitability among the long-term strategies specific to Alternatives B, C, D, and E, suggesting that experimental elements identified in Table 4.1-1 such as HFEs, low summer flows, TMFs, and hydropower improvement flows would have little effect on mainstem water temperature regimes during periods of the year considered most important for spawning and egg incubation by native species. Rather, differences in temperature suitability for native fish under the various long-term strategies appear to be more related to differences in the seasonal patterns of releases and the effects of those patterns on seasonal temperatures. Thus, the reduction in modeled temperature suitability under Alternative F at RM 225 reflects the higher flows expected to occur under this alternative during spring and early summer months when native fish are expected to spawn; those higher flows would result in temperatures less suitable for spawning and egg incubation.

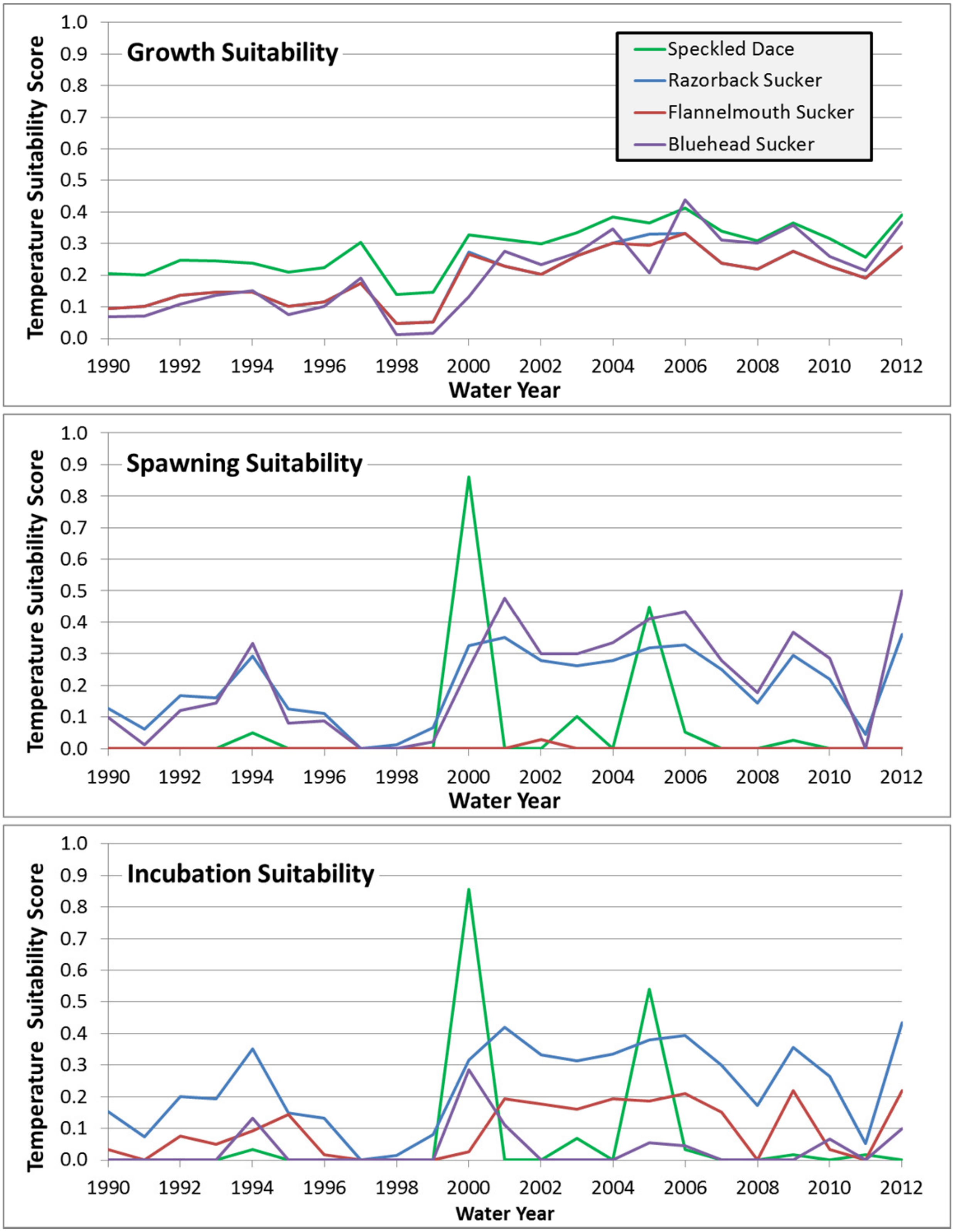

FIGURE F-27 Annual Temperature Suitability Scores for Growth, Spawning, and Egg Incubation of Native Fish Species at RM 225 Based on Modeled Water Temperatures for Water Years 1990–2012

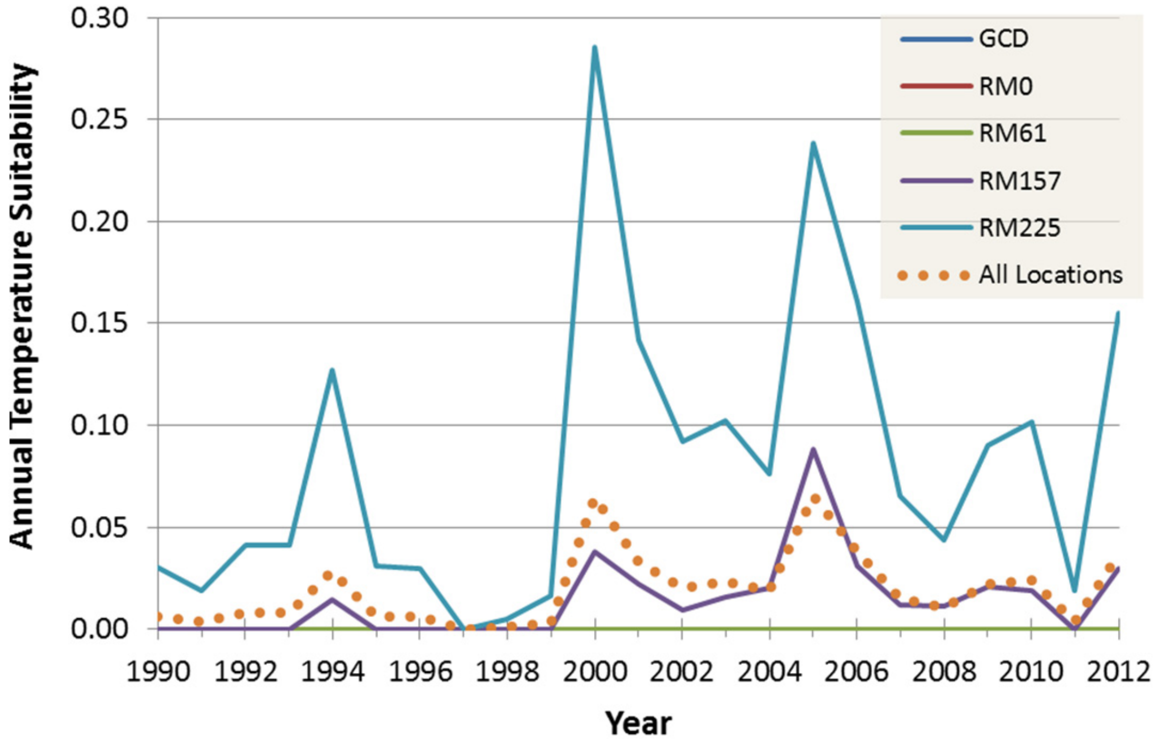

FIGURE F-28 Annual Temperature Suitability Scores for Native Fish by Assessment Location Based on Modeled Water Temperatures for Water Years 1990–2012

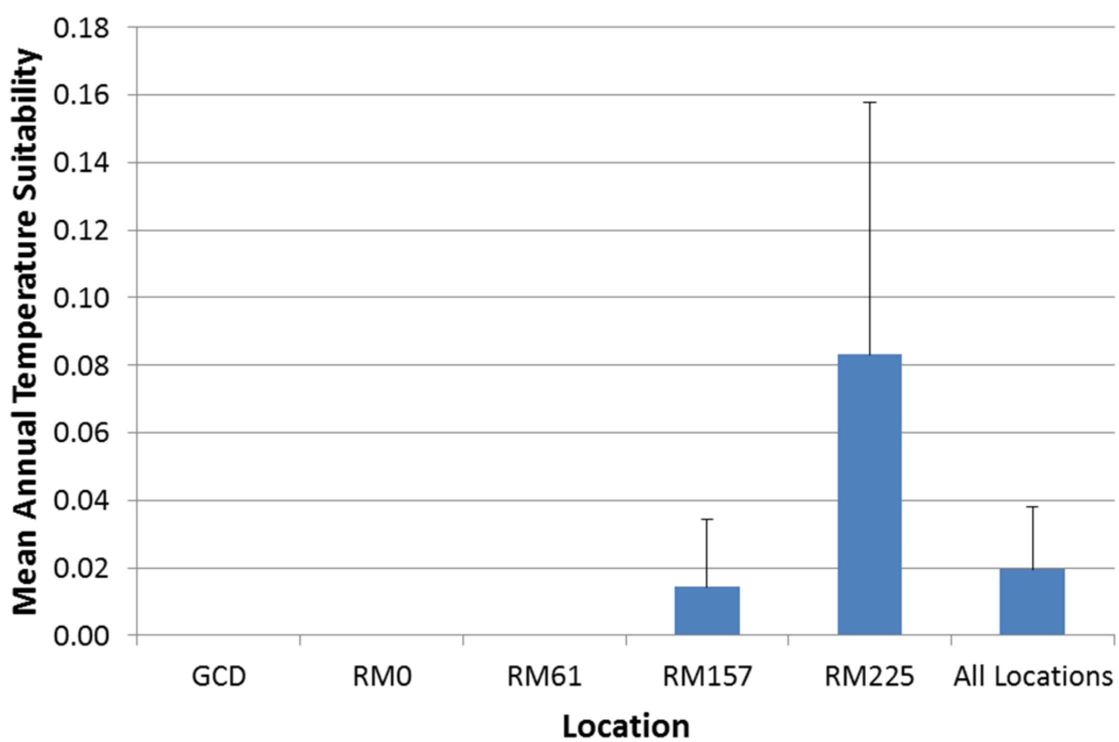

FIGURE F-29 Mean (±SD) Annual Overall Temperature Suitability for Native Fish by Assessment Location Based on Modeled Water Temperatures for Water Years 1990–2012

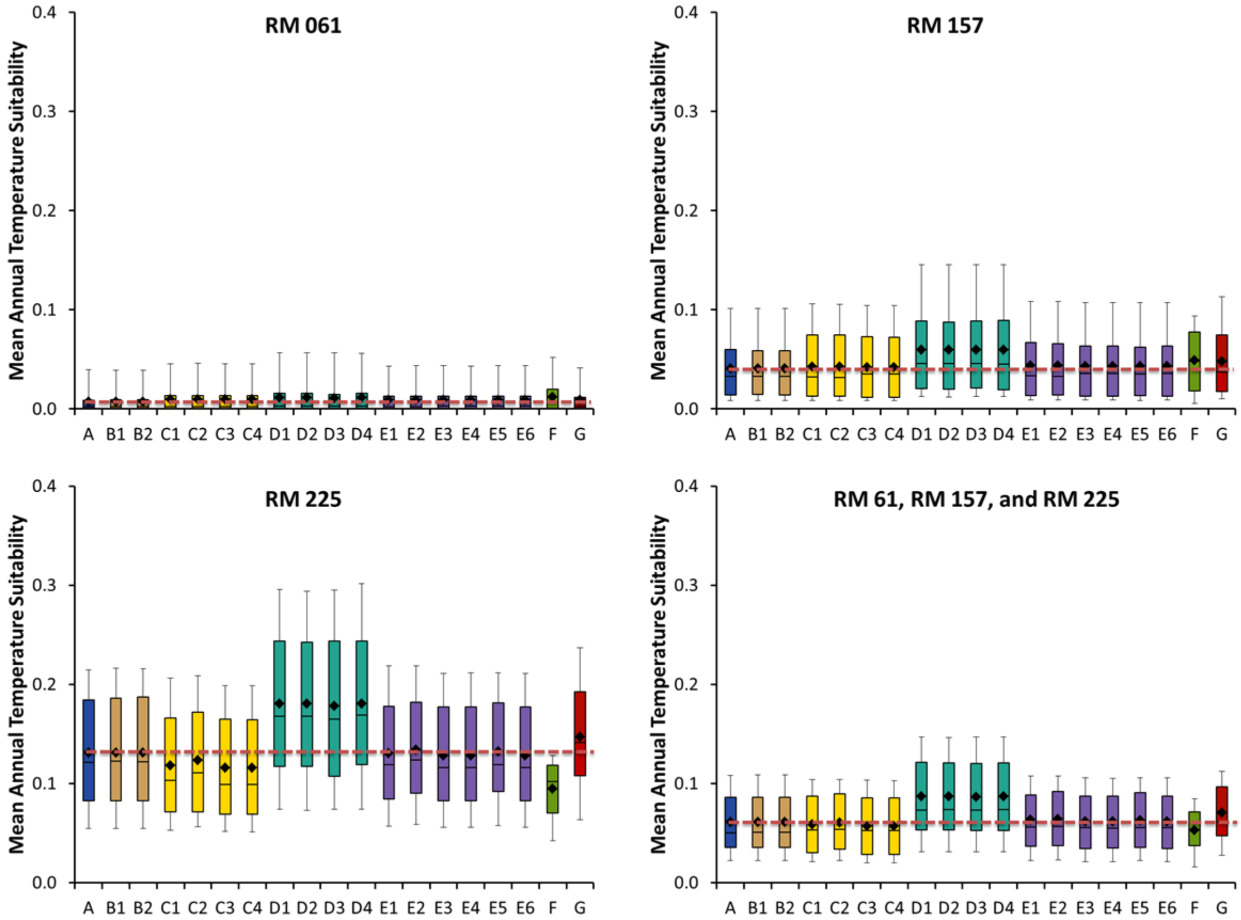

FIGURE F-30 Mean Annual Mainstem Temperature Suitability for Native Fish under LTEMP Alternatives and Long-Term Strategies at RM 61, RM 157, and RM 225, and Overall Mean for RM 61–225 (The graph shows the mean, median, 75th percentile, 25th percentile, minimum, and maximum values for 21 hydrology scenarios and three sediment scenarios. Means were calculated as the average for all years within each of the 21 hydrology runs. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum; horizontal dashed line identifies mean value for Alternative A.)

F.4.4 Nonnative Fish

The temperature suitability model for nonnative fish evaluates how well alternatives provide mainstem water temperatures suitable for spawning, egg incubation, and growth of six species of coldwater (brown trout [*Salmo trutta*], rainbow trout) and warmwater (channel catfish [*Ictalurus punctatus*], green sunfish [*Lepomis cyanellus*], smallmouth bass [*Micropterus dolomieu*], and striped bass [*Morone saxatilis*]) nonnative fish. In order to account for changes in water temperatures as water released from Glen Canyon Dam travels downstream, evaluations of temperature suitability were conducted for the five mainstem Colorado River locations identified in Table F-11. As described in Section F.4.1, the time series of water temperatures used as inputs for these locations were generated using a water temperature model developed by Wright et al.

(2009). The calculated suitability values for various water temperatures for successful spawning, egg incubation, and growth of the six nonnative fish species are depicted in Figure F-31. The months encompassing the spawning and egg incubation periods for each of the six nonnative fish species are indicated in Figure F-32. The annual suitability of daily temperatures for growth is calculated as the mean of daily suitability values for the entire water year (October through September). The overall means of temperature suitability values for the coldwater and warmwater nonnative species groups were examined separately.

F.4.4.1 Historic Temperature Suitability for Nonnative Fish

Historic temperature suitability of mainstem water temperatures for the six nonnative fish species was examined using modeled water historic temperatures at the five evaluation locations for a 23-year period from October 1, 1989, through September 30, 2012 (water years 1990–2012), as the temperature inputs (Figure F-26). Figure F-33 presents the annual temperature suitability scores for spawning, incubation, and growth of the six nonnative fish species based upon the modeled historic temperatures for water years 1990–2012 at RM 225 (Diamond Creek). The mean annual temperature suitability scores for each species and temperature group for the five river locations are presented in Figure F-34. The overall means of annual suitability scores for the coldwater and warmwater nonnative fish species groups across all river locations during the 1990–2012 water years are presented in Figure F-35.

F.4.4.2 Results for LTEMP Alternatives

In general, temperature suitability for coldwater nonnative species (i.e., brown and rainbow trout) would be similar among most of the long-term strategies at most locations downstream of Glen Canyon Dam and would be remain similar to current conditions based on comparisons to Alternative A (Figure F-36). Because of the effects of the timing and magnitude of peak and base flow releases on water temperatures, temperature suitability would be slightly greater under Alternative F than other long-term strategies at the confluence with the Little Colorado River (RM 61) and lower under Alternative F than other long-term strategies for locations farther downstream; however, those differences are very small and may not be biologically significant. Although main channel temperature regimes at and downstream of RM 61 appear to become more suitable for trout species than at locations closer to the dam (Figure F-36), the abundance of trout is known to be lower at those locations (based on sampling), suggesting that other habitat characteristics (e.g., substrate composition and water clarity) may be less suitable at these downstream locations. Because inclusion of flow actions such as HFEs, TMFs, and low summer flows had only minor influences on modeled monthly mainstem water temperatures during periods of the year considered most important for spawning and egg incubation by trout, these flow actions have little effects on modeled mainstem temperature suitability and would not alter relative suitability for coldwater nonnative species among the long-term strategies (Figure F-36).

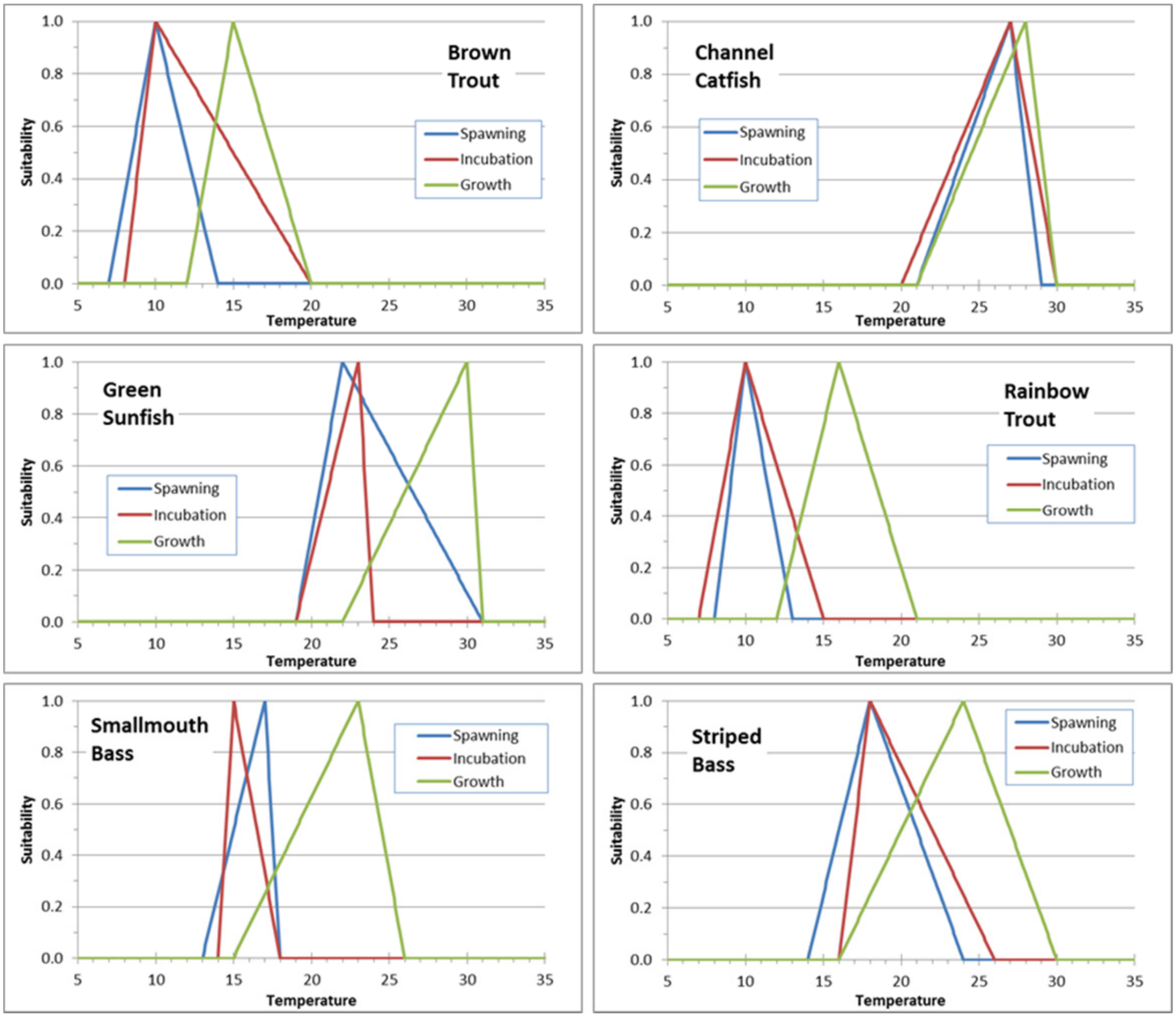

FIGURE F-31 Suitability of Water Temperatures (°C) for Spawning, Egg Incubation, and Growth of Nonnative Fish Species (Source: Valdez and Speas 2007)

Temperature suitability at the various main channel locations was modeled for the four nonnative warmwater species considered to be representative of the warmwater nonnative fish community (smallmouth bass, green sunfish, channel catfish, and striped bass). In general, the estimated average main-channel temperature suitability for these nonnative fish did not differ greatly among the long-term strategies, and was low under all long-term strategies (Figure F-37). The modeled temperature suitability indicated that temperature conditions would be most suitable for warmwater nonnative species at locations farther downstream from Glen Canyon Dam (e.g., RM 157 and RM 225) compared to upstream locations (e.g., RM 0 and RM 61); this agrees with past surveys that have found more warmwater nonnative fish species in those areas. Relative to current conditions (as exemplified by Alternative A), the temperature suitability model indicated that the long-term strategies for Alternative C (i.e., C1, C2, C3, and C4) and Alternative F have the greatest potential to improve conditions for warmwater nonnative fish at

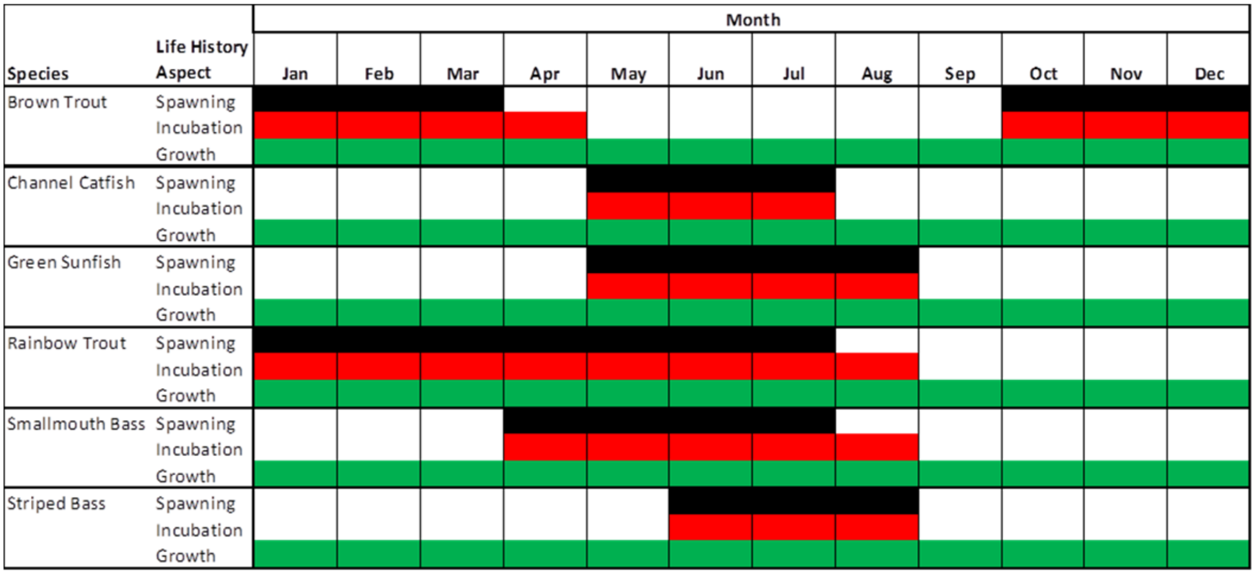

FIGURE F-32 Months during Which Temperature Suitability for Specific Life History Aspects Were Calculated for Nonnative Fish Species

locations downstream of RM 157, which could result in increased numbers and a greater potential for upstream spread of warmwater nonnative fish species. As described above for coldwater fish species, inclusion of flow actions such as HFEs, TMFs, and low summer flows had only minor influences on modeled monthly mainstem water temperatures during periods of the year considered most important for spawning and egg incubation by nonnative warmwater species. As a consequence, the various experimental elements associated with the long-term strategies (Table 4.1-1) would be expected to have little effect on mainstem temperature suitability for warmwater nonnative species (Figure F-37). Rather, as identified for native fish in Section F.4.3.2, differences among alternatives appear to be more related to differences in the seasonal patterns of releases and the effects of those patterns on seasonal temperatures.

F.4.5 Aquatic Parasites

The temperature suitability model for aquatic parasite species evaluates how well alternatives provide mainstem water temperatures suitable for host activity for and infestation by four species (Asian tapeworm [*Bothriocephalus acheilognathi*], anchor worm [*Lernaea cyprinacea*], trout nematode [*Truttaedacnitis truttae*], and whirling disease [*Myxobolus cerebralis*]) that could parasitize fish in the Colorado River downstream of Glen Canyon Dam. In order to account for changes in water temperatures as water released from Glen Canyon Dam travels downstream, evaluations of temperature suitability were conducted for the mainstem Colorado River locations identified in Table F-11. As described in Section F.4.1, the time series of water temperatures used as inputs for these locations were generated using a water temperature model developed by Wright et al. (2009).

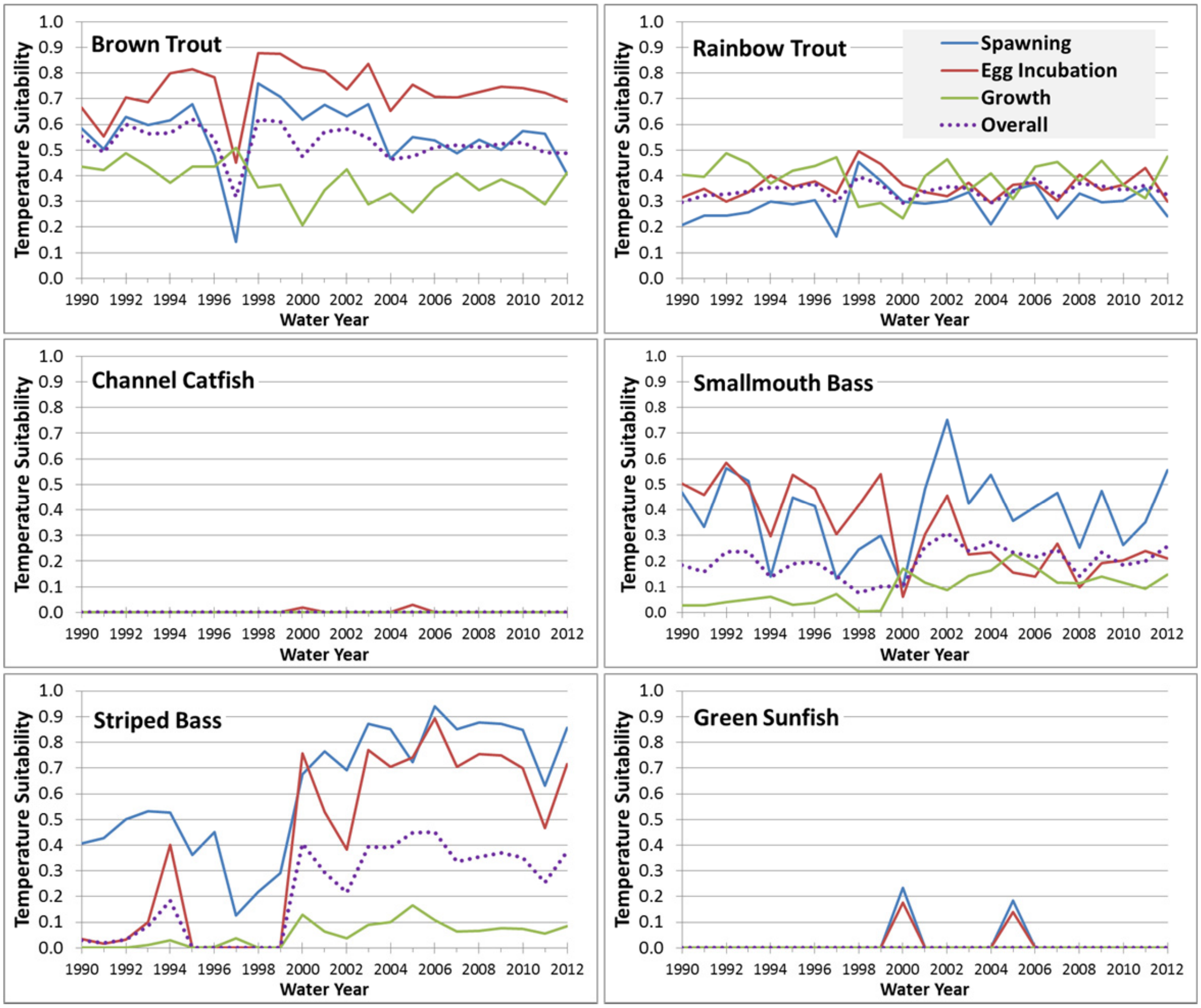

FIGURE F-33 Annual Temperature Suitability Scores for Spawning, Incubation, and Growth of Nonnative Fish Species at RM 225 (Diamond Creek) Based on Modeled Temperatures for Water Years 1990 to 2012

The calculated suitability values at various water temperatures for host activity and infestation rates of the four parasite species is depicted in Figure F-38. It was assumed that evaluation of temperature suitability across the entire water year (rather than just a portion of the year) was relevant for both of the parasite life history components. The geometric mean of the annual temperature suitability values for host activity and infestation was used as an indicator of the annual overall suitability for each parasite species and served as the indicator of the potential for each of the parasite species to become problematic at a particular downstream location. The combined mean of the annual suitability scores for all four parasite species was used as an indication of the overall suitability of each year’s temperature regime for the group of parasite species at each downstream location. The mean of the group means for all of the downstream locations was calculated as an indication of overall relative suitability of the temperature regime

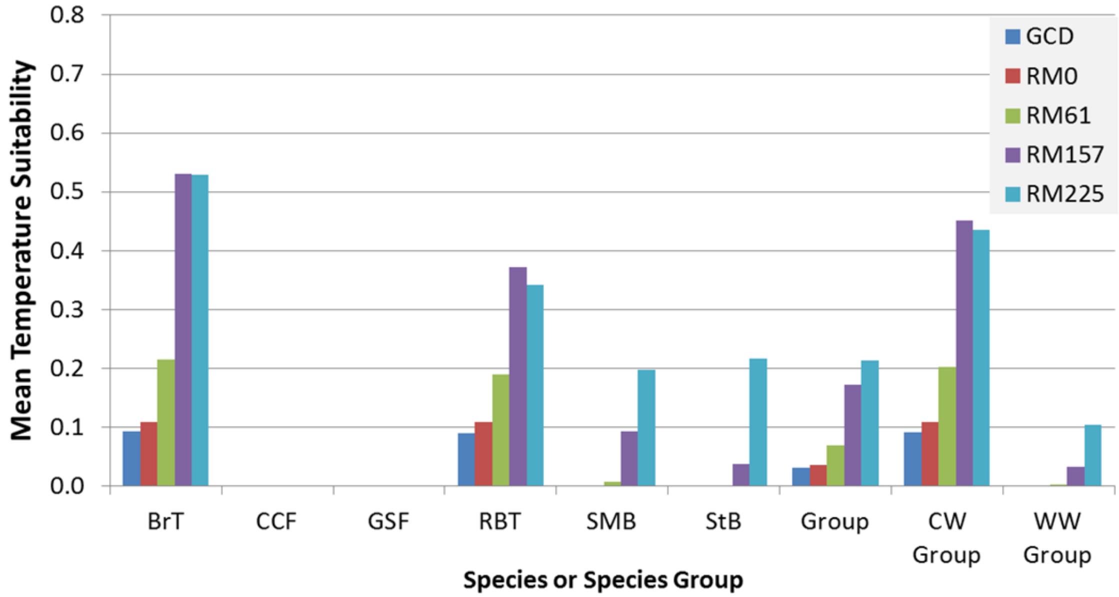

FIGURE F-34 Mean Annual Temperature Suitability Scores for Nonnative Fish Species and for Temperature Groups by River Location Based on Modeled Water Temperatures for Water Years 1990–2012 (BrT = brown trout; CCF = channel catfish; GSF = green sunfish; RBT = rainbow trout; SMB = smallmouth bass; StB = striped bass; Group = combined coldwater and warmwater; CW = coldwater; WW = warmwater)

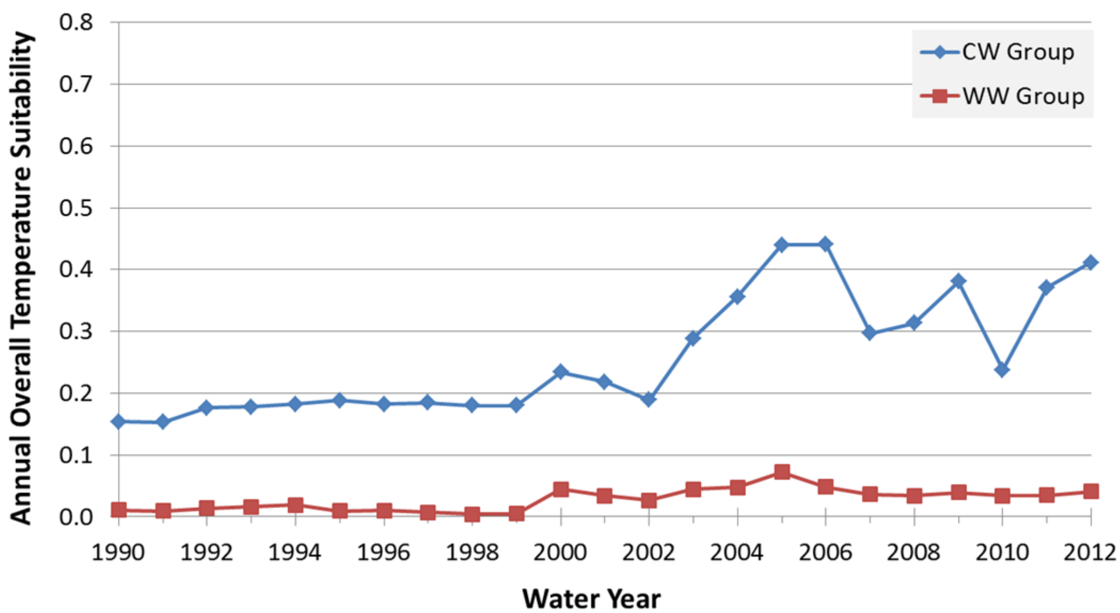

FIGURE F-35 Mean Annual Overall Temperature Suitability Scores for Coldwater (CW) and Warmwater (WW) Nonnative Fish Species Groups Based on Modeled Historic Temperatures for Water Years 1990–2012

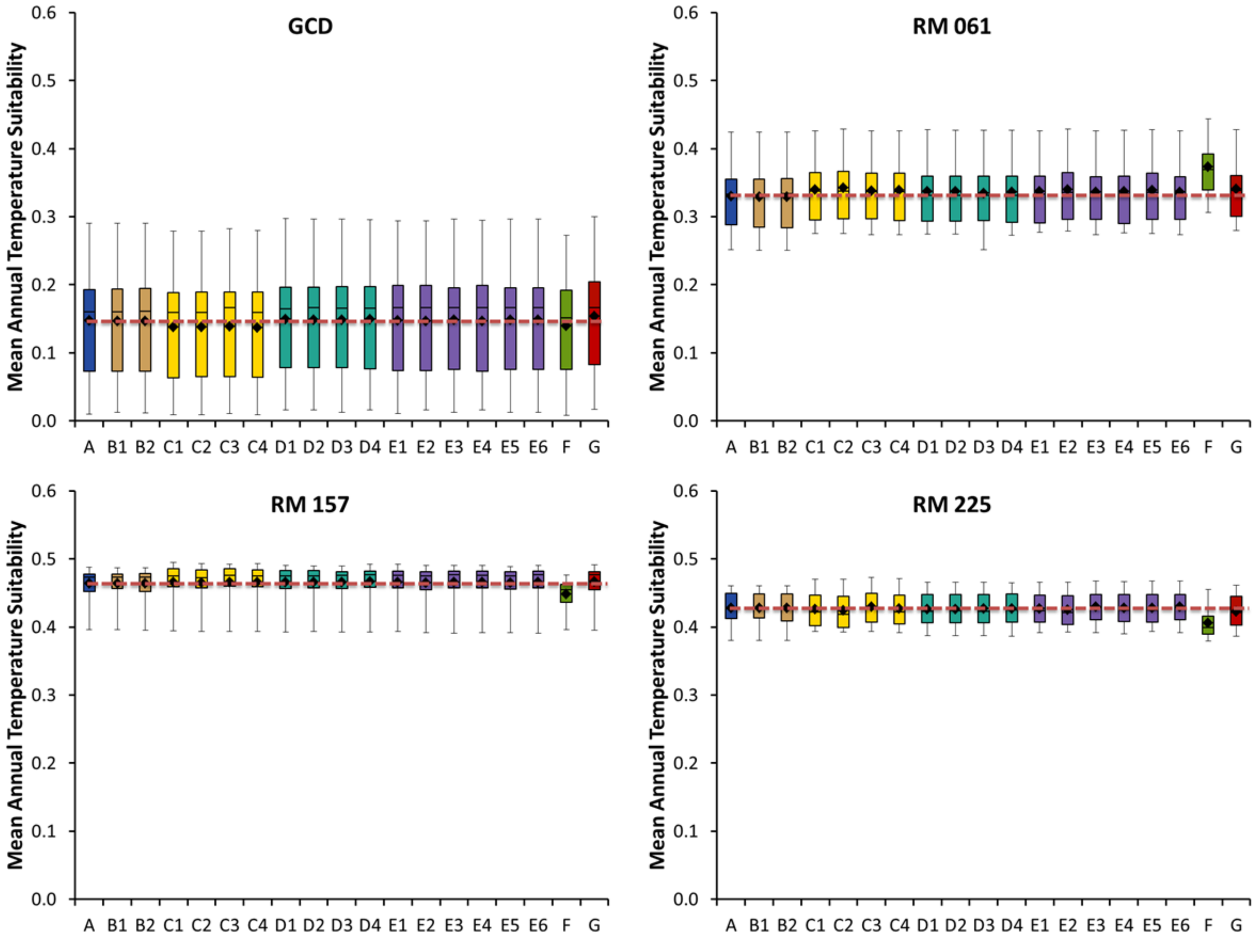

FIGURE F-36 Mean Annual Mainstem Temperature Suitability for Coldwater Nonnative Fish (brown trout and rainbow trout) under LTEMP Alternatives and Long-Term Strategies at RM –15 (Glen Canyon Dam, GCD) RM 61, RM 157, and RM 225 (The graph shows the mean, median, 75th percentile, 25th percentile, minimum, and maximum values for 21 hydrology scenarios and three sediment scenarios. Means were calculated as the average for all years within each of the 21 hydrology runs. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum; horizontal dashed line identifies mean value for Alternative A.)

within a particular year for parasite species in the mainstem Colorado River downstream of Glen Canyon Dam.

F.4.5.1 Historic Temperature Suitability for Aquatic Parasites

Historic temperature suitability of mainstem water temperatures for the four aquatic parasite species was examined using modeled water historic temperatures at the five evaluation locations for a 23-year period from October 1, 1989, through September 30, 2012 (water years 1990–2012), as the temperature inputs (Figure F-26). Figure F-39 presents the annual

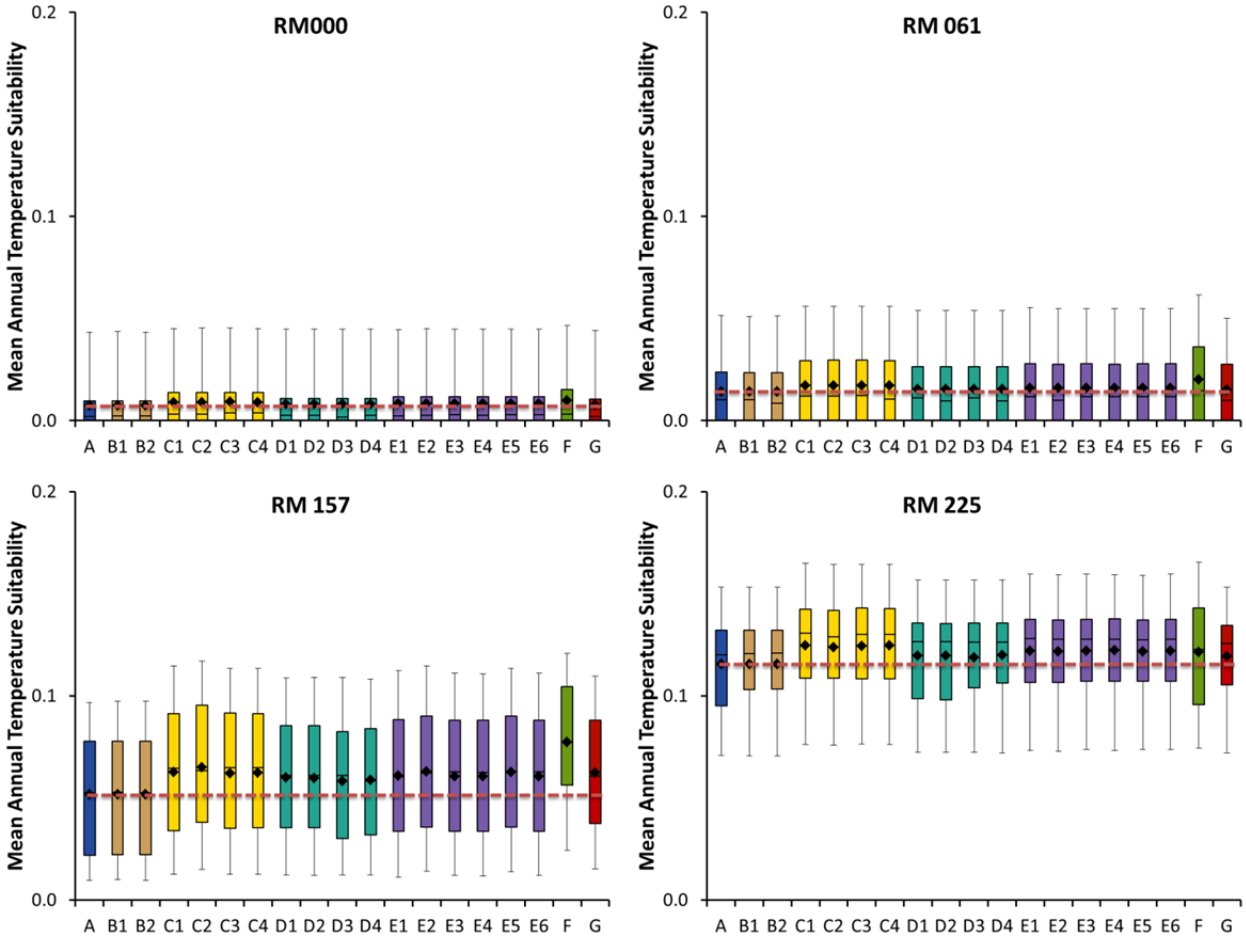

FIGURE F-37 Mean Annual Mainstem Temperature Suitability for Warmwater Nonnative Fish (channel catfish, green sunfish, smallmouth bass, and striped bass) under LTEMP Alternatives and Long-Term Strategies at RM 0, RM 61, RM 157, and RM 225 (The graph shows the mean, median, 75th percentile, 25th percentile, minimum, and maximum values for 21 hydrology scenarios and three sediment scenarios. Means were calculated as the average for all years within each of the 21 hydrology runs. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum; horizontal dashed line identifies mean value for Alternative A.)

temperature suitability scores for host activity and infestation rates of the parasite species based upon the modeled historic temperatures for water years 1990–2012 at RM 225 (Diamond Creek). The mean annual temperature suitability scores for each species and temperature group for the five river locations are presented in Figure F-40. The overall means of modeled annual suitability scores for the coldwater and warmwater nonnative fish species groups across all river locations during the 1990–2012 water years are presented in Figure F-41.

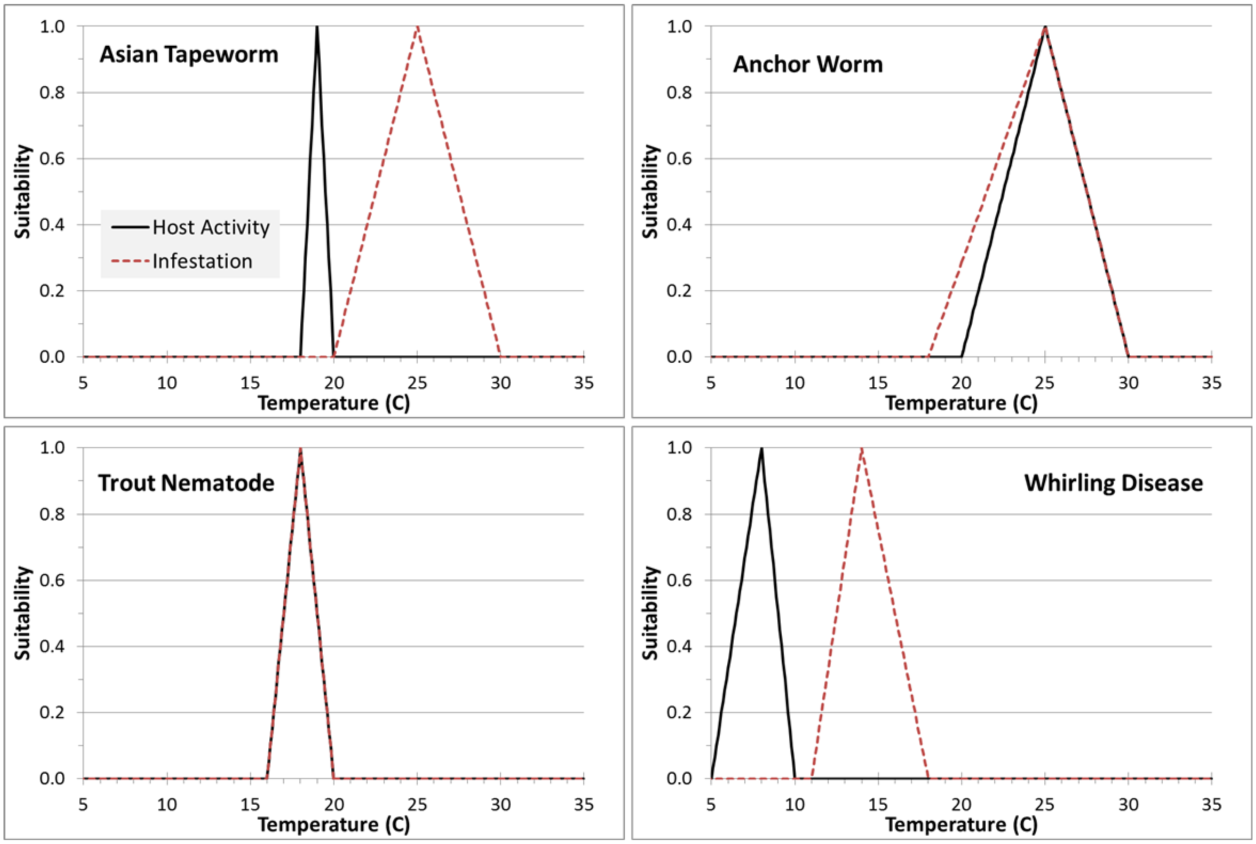

FIGURE F-38 Suitability of Various Water Temperatures for Host Activity and Infestation Rates of Parasite Species (Source: Valdez and Speas 2007)

F.4.5.2 Results for LTEMP Alternatives

Temperature suitability for the four aquatic parasite species (Asian tapeworm, anchor worm, trout nematode, and whirling disease) under the LTEMP alternatives and long-term strategies was modeled for various locations downstream from Glen Canyon Dam. Modeling indicated that temperature suitability for the aquatic parasite species would generally be very low under all long-term strategies and would be comparable to the suitability under current operations as represented by Alternative A (no-action alternative; Figure F-42). As a consequence, the relative distributions of aquatic parasites or the effects of aquatic parasites on survival and growth of native fish or trout species would not be expected to change relative to current conditions under any of the long-term strategies. Under current conditions, population-level effects of parasites on survival and growth of native fish or trout have not been observed. Inclusion of flow actions such as HFEs, TMFs, and low summer flows had only minor influences on modeled monthly mainstem water temperatures during periods of the year considered most important for spawning and egg incubation by native fish. As a consequence, these flow actions are expected to have minor effects on temperature suitability for the parasite species group and would not alter the relative suitability among the long-term strategies.

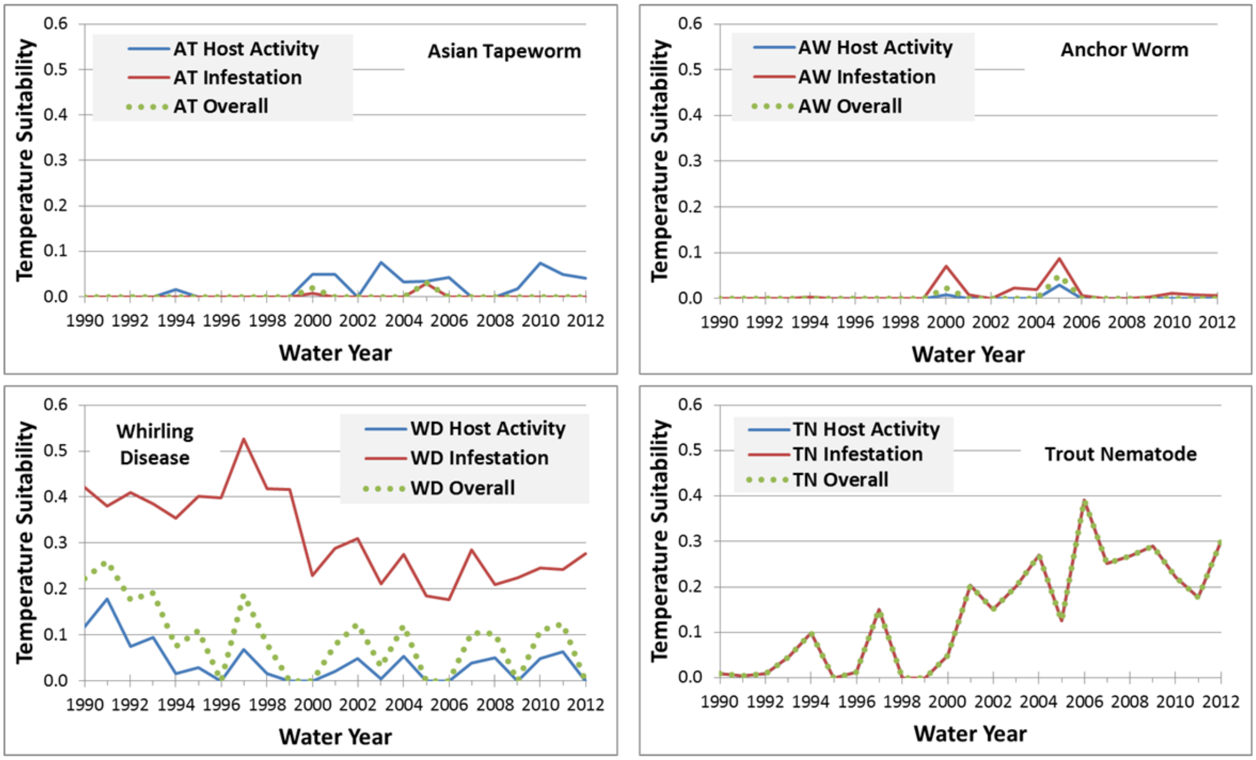

FIGURE F-39 Annual Temperature Suitability Scores for Parasite Species at RM 225 (Diamond Creek) Based on Modeled Water Temperatures for Water Years 1990–2012 (AT = Asian tapeworm; AW = anchor worm; TN = trout nematode; and WD = whirling disease)

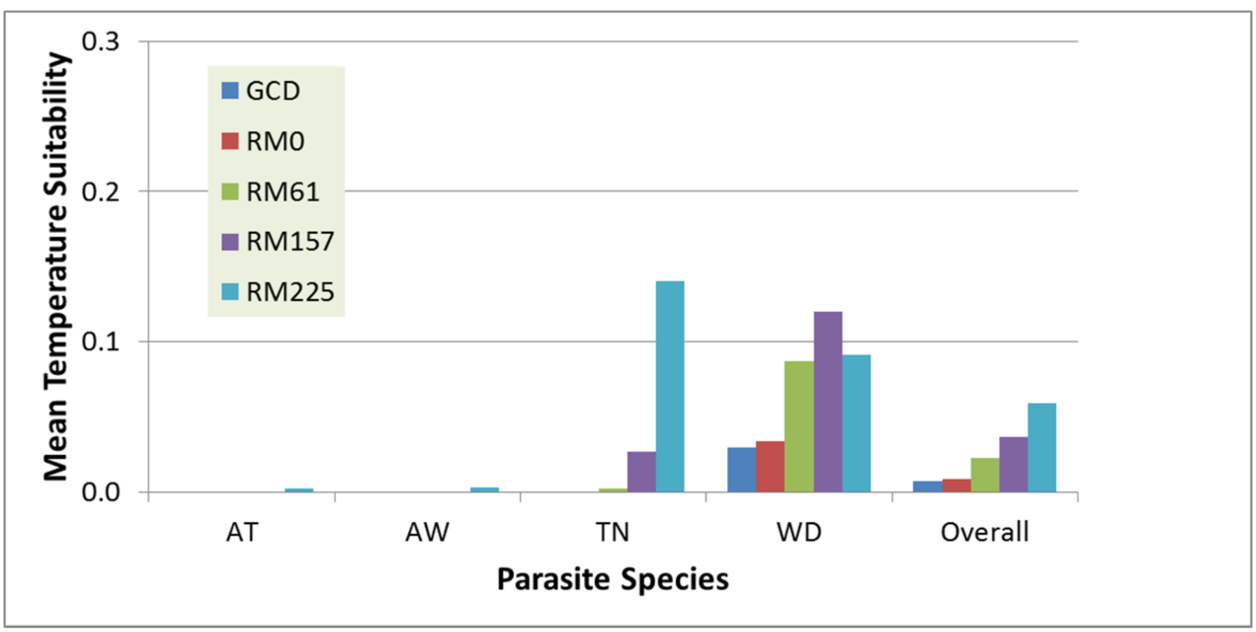

FIGURE F-40 Mean Annual Temperature Suitability Scores for Parasite Species by River Location Based on Modeled Water Temperatures for Water Years 1990–2012 (AT = Asian tapeworm; AW = anchor worm; TN = trout nematode; and WD = whirling disease)

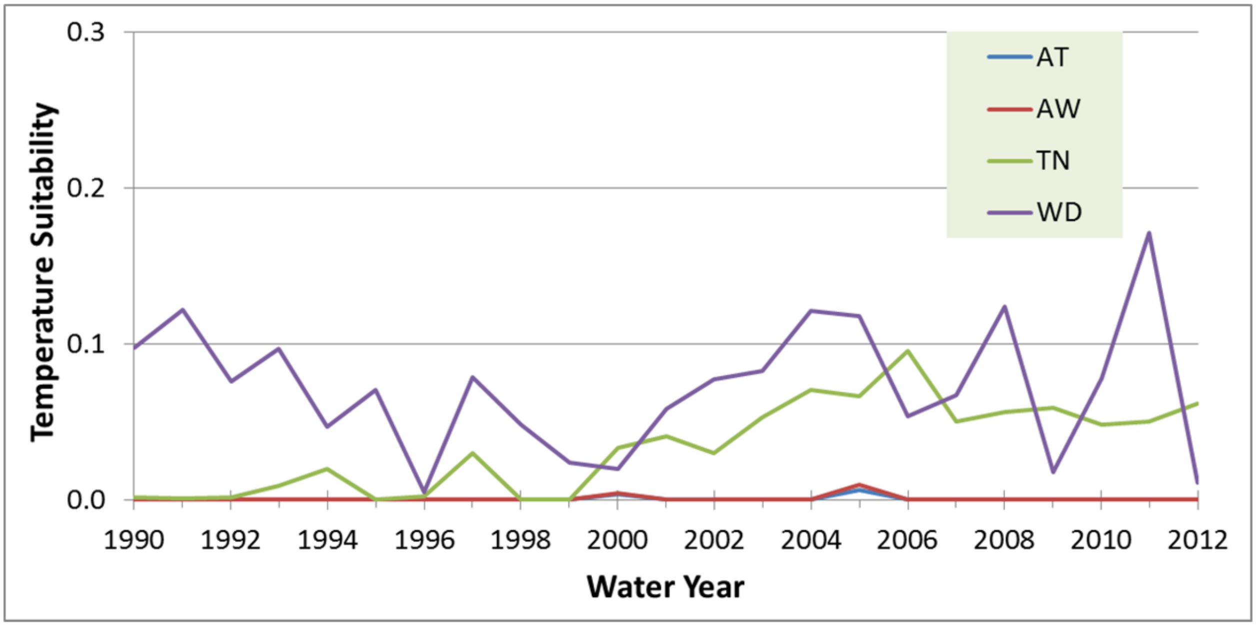

FIGURE F-41 Overall Means of Annual Suitability Scores for Parasite Species Across All River Locations during the 1990–2012 Water Years (AT = Asian tapeworm; AW = anchor worm; TN = trout nematode; and WD = whirling disease)

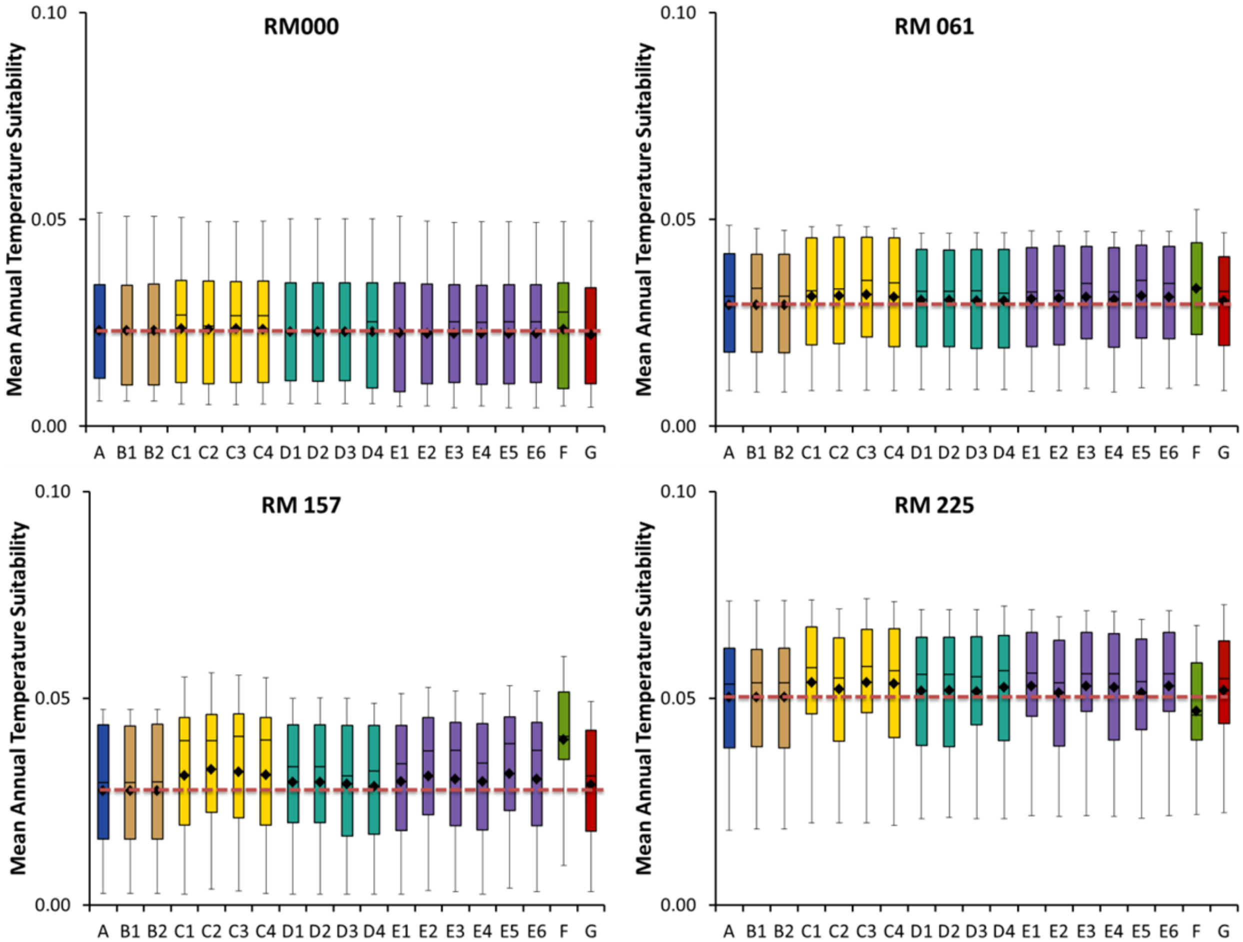

FIGURE F-42 Overall Modeled Mean Annual Temperature Suitability under LTEMP Alternatives and Long-Term Strategies for Aquatic Fish Parasites (Asian tapeworm, anchor worm, trout nematode, and whirling disease) at Four Locations Downstream of Glen Canyon Dam (The graph shows the mean, median, 75th percentile, 25th percentile, minimum, and maximum values for 21 hydrology scenarios and three sediment scenarios. Means were calculated as the average for all years within each of the 21 hydrology runs. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum; horizontal dashed line identifies mean value for Alternative A.)

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APPENDIX G:

VEGETATION TECHNICAL INFORMATION AND ANALYSIS

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APPENDIX G:

VEGETATION TECHNICAL INFORMATION AND ANALYSIS

G.1 ANALYSIS METHODS

The analysis of impacts on plant communities is primarily based on the evaluation of four performance metrics that were developed for the Long-Term Experimental and Management Plan (LTEMP) assessment process. The metrics are calculated using the results of an existing state and transition model for Colorado River riparian vegetation downstream from Glen Canyon Dam. Model details are described in Ralston et al. (2014). The four metrics are as follows:

- Relative change in cover of native vegetation community types (other than arrowweed[1]) on sandbars and channel margins using the total percent increase in native states (change in native cover = $cover_{final}/cover_{initial}$).

- Relative change in diversity of native vegetation community types (other than arrowweed) on sandbars and channel margins using the Shannon-Weiner Index for richness/evenness (change in diversity = $diversity_{final}/diversity_{initial}$).

- Relative change in the ratio of native (other than arrowweed)/nonnative dominated vegetation community types on sandbars and channel margins (change in native/nonnative ratio = $ratio_{final}/ratio_{initial}$).

- Relative change in the arrowweed state on sandbars and channel margins using the total percent decrease in arrowweed states (Change in arrowweed = $arrowweed_{initial}/arrowweed_{final}$).

These performance metrics were developed from the resource goal for riparian vegetation downstream from Glen Canyon Dam: *Maintain native vegetation and wildlife habitat, in various stages of maturity that is diverse, healthy, productive, self-sustaining, and ecologically appropriate*.

The state and transition model was developed to compare the effects of various flow regimes on Colorado River riparian vegetation. Seven vegetation states are used in the model to represent plant community types found along the river on sandbars and channel margins in the new high-water zone and fluctuation zone. Species associated with a state respond similarly to Colorado River hydrologic factors such as depth, timing, and duration of inundation. These states and the plant species associated with each are given in Table G-1. The model and data used to calculate performance metrics are based on vegetation studies conducted within Grand Canyon National Park and may have limited application to riparian vegetation communities within Glen

[1] This species was selected to be excluded from the native species metrics and to be a fourth metric. It is managed differently than other native species because of its tendency to rapidly establish on sandbars to the exclusion of other species.

Canyon. The model consists of six submodels based on landforms: lower separation bar, upper separation bar, lower reattachment bar, upper reattachment bar, lower channel margin, and upper channel margin. Upper and lower bars are divided at the 25,000 cfs flow stage.

The model uses the daily maximum flow from the GTMax-Lite 2 hydrograph (GTMax-Lite 2 includes hourly flows for the entire 20-year flow period); it does not include daily fluctuations (the range in flows within a day). A total of 63 hydrology-sentiment trace combinations were included in the analysis of each alternative and long-term strategy. Within each run of each alternative, the model identifies the occurrence of hydrologic events, such as spill flows, spring and fall high-flow experiments (HFEs), extended low flows, extended high flows, and growing or non-growing seasons without extended high or low flows, occurring during the growing season (May–September) or non-growing season (October–March) (see Table G-2). The model then records transitions between vegetation states, based on a set of rules developed for each submodel, driven by these hydrologic events. The model includes a subset of states and transition rules for each bar type and channel margin type. The transition rules for the upper portions of the bars and channel margin are the same because of the similarity of plant community types and responses to flow characteristics. The transition rules are based on the effects of scouring, drowning, desiccation, and sediment deposition on riparian plant species. The interrelationships among vegetation states were developed primarily from published vegetation studies based on data collected in Grand Canyon National Park (see Ralston et al. 2014 and citations therein). A subject matter expert team refined the transitions based on extensive field experience in the Colorado River riparian system. Transition rules for the submodels are given in Table G-3. Although the model is a simplification of the complexities of the riparian ecosystem, it is a valuable tool in estimating the changes in riparian vegetation under a variety of flow regimes.

Model results include the total number of years each state occurs for the 20-year period of the model run, according to each potential starting state in each submodel (i.e., the number of years each feature is in each state, based on the transition rules). Each model run starts with each potential state of each submodel, shown in Table G-1. For example, the lower Reattachment Bar submodel uses five different starting states for each hydrologic trace: bare sand, *Phragmites australis* Temperate Herbaceous Vegetation, *Equisetum hyemale* Herbaceous Vegetation, Tamarisk Temporarily Flooded Shrubland, and *Pluchea sericea* Seasonally Flooded Shrubland. Therefore, five model runs, each with a different starting state, are made with the Reattachment Bar submodel for each trace.

G.1.1 Old High-Water Zone Analysis

Plant communities of the old high-water zone are not included in the riparian state and transition model. Therefore, a qualitative assessment was conducted to evaluate impacts of alternatives. The old high-water zone vegetation is located at high flow stage elevations (above 60,000 cfs, but primarily from about 100,000 to approximately 200,000 cfs), well above the level of current dam operations. Dam operations, other than HFEs, are limited to 31,500 cfs flows (generally will not exceed 25,000 cfs), and HFEs do not exceed 45,000 cfs.

None of the alternatives considered would include flows sufficient to maintain these pre-dam plant communities. HFEs could potentially provide occasional soil moisture to some older deep-rooted plants located in the old high-water zone. Dam releases can affect water availability for plants at elevations up to approximately 15,000 cfs above discharge levels (Melis et al. 2006; Ralston 2005). Alternatives with more frequent spring HFEs—such as Alternative F, with annual spring HFEs, or Alternative G; Alternative C, long-term strategies C1 and C2; and Alternative D, long-term strategies D1–D4, all with considerably more spring HFEs than Alternative A—may result in higher survival rates of plants at lower elevations of the old high-water zone than under Alternative A. Spill flows (between 45,000 and 85,000 cfs) would provide soil moisture to old high-water zone plants; however, these have not occurred since the mid-1980s. Periodic spill flows could occur within the 20-year period of this evaluation, but would likely be infrequent and would occur equally under all alternatives. Because of a lack of sufficiently high flows and nutrient-rich sediment, mortality of pre-dam plants within this zone has been occurring for decades, along with a lack of seedling establishment for some species, such as mesquite and hackberry (Kearsley et al. 2006; Anderson and Ruffner 1987; Webb et al. 2011). Because of generally continued low soil moisture and lack of recruitment opportunities under all alternatives, the upper margins of this zone would be expected to continue moving downslope, with a continued narrowing of this zone. Desert species occurring on the pre-dam flood terraces and aeolian deposits above the Old High-Water Zone would increasingly establish within this zone.

G.1.2 New High-Water Zone

The four metrics, (1) relative change in cover of native vegetation community types, (2) relative change in diversity of native vegetation community types, (3) relative change in the ratio of native/nonnative dominated vegetation community types, and (4) relative change in the arrowweed state, were calculated from the model results for each alternative and long-term strategy. The four native-dominated states are *Phragmites australis* Temperate Herbaceous Vegetation, *Salix exigua-Baccharis emoryi* Shrubland/*Equisetum laevigatum* Herbaceous Vegetation, *Populus fremontii*/*Salix exigua* Forest, and *Prosopis glandulosa* var. *torreyana* Shrubland. Two of these states, both of which represent wetland community types, are further discussed below. Although arrowweed is a native species, because of its invasive characteristics and tendency to form monocultures, the *Pluchea sericea* Seasonally Flooded Shrubland state is excluded from the native states in the performance metrics.

Model results were used to calculate the performance metrics for each alternative/long-term strategy using the sum of years of each of the states for all six models. This value is then compared to the number of years each state would have accumulated if the current condition was maintained (i.e., if no transitions occurred and each of the seven states remained the same for the full 20 years of the model run). This proportion was then multiplied by the acreage of mapped cover types from the NPS Vegetation Map of Grand Canyon National Park (Table G-4) corresponding to the seven model states (Table G-5). This final acreage and the initial mapped acreage were then used to calculate the performance metrics.

The results for the four metrics were then summed to derive a final score for each alternative long-term strategy. Alternatives with higher scores were considered to have come closer to achieving the resource goal.

The 63 hydrology-sediment trace combinations used in the model runs were developed from the historical record (see Section 4.1 of the DEIS for a detailed description). Twenty-one potential Lake Powell inflow scenarios for the 20-year LTEMP period were sampled from the 105-yr historic record (water years 1906–2010), producing 21 hydrology traces for analysis. In addition, three 20-year sequences of sediment input from the Paria River sediment record (water years 1964–2013) were analyzed. In combination, the analysis considered 63 possible hydrology-sediment scenarios. An assumption underlying the model results is that future river flows will be similar to past flows. To examine the effect of potential climate change, each of the traces used in the model runs was then differentially weighted (see Section 4.17.1.2). Weights were developed based on climate change projections of the 2012 Colorado River Basin Water Supply and Demand Study (Reclamation 2012). These assigned weights thus reflect the likelihood of occurrence of each hydrology trace under potential future climate change, emphasizing the drier scenarios. The model result for each trace was then multiplied by the assigned weight.

G.1.2.1 Native Cover Metric

Relative change in cover of native vegetation community types (other than arrowweed) on sandbars and channel margins using the total percent increase in native states (change in native cover = $cover_{final}/cover_{initial}$).

The results for the Native Cover metric based on historical flows are shown in Figure G-1. The two highest-scoring long-term strategies, E6 and E3, are significantly different from the others (differences between means of the 63 traces based on a three-factor ANOVA followed by Tukey's Studentized Range [HSD] Test) but not from each other. Results under projected climate change are similar to those for historical flows (all alternatives score slightly higher) and are shown in Figure G-2; thus the relative performance of each alternative under climate change would be similar to that modeled under historical conditions.

To illustrate the relative change in native cover, the modeled acreage changes for several alternative/long-term strategies are shown in Table G-6.

Native states tend to increase with growing and non-growing seasons without extended high or low flows. Bare Sand, Tamarisk Temporarily Flooded Shrubland, and *Pluchea sericea* Seasonally Flooded Shrubland tend to increase with extended high and extended low flows. The effect of differences between hydrologic traces is greater than the effect of differences between alternatives.

G.1.2.2 Native Diversity Metric

Relative change in diversity of native vegetation community types (other than arrowweed) on sandbars and channel margins using the Shannon-Weiner Index for richness/evenness (change in diversity = diversity$_{final}$/diversity$_{initial}$).

The Native Diversity metric is calculated using the Shannon-Weiner Index for richness/evenness: $-\Sigma(p_i)(\log_2 p_i)$ where p_i is the proportion of the *i*-th state of the total native cover. The calculations use the initial mapped cover and final (modeled) cover of each of the four native-dominated states. The results for the Native Diversity metric based on historical flows are shown in Figure G-3; the two highest scoring alternatives—Alternative E, long-term strategy E4, and Alternative B, long-term strategy B1—are not significantly different from each other (differences between means based on a three-factor ANOVA followed by Tukey's Studentized Range [HSD] Test); long-term strategy B1 is not significantly different from long-term strategies D3 and D2. Results under projected climate change are similar to those for historical flows, with 11 alternatives showing a slight increase and eight with a slight decrease, and are shown in Figure G-4; thus the performance of each alternative under climate change would be similar to that modeled under historical conditions. The results for all alternatives include all states. Therefore, there is no difference in the number of states between alternatives; diversity is increased by the evenness of states. For example, long-term strategy B2 and Alternative F, which are somewhat lower scoring, have a low representation of the *Phragmites australis* Temperate Herbaceous Vegetation state, while long-term strategies B1 and E4, somewhat higher scoring, have a relatively high representation of that state. The transition to the *Phragmites australis* Temperate Herbaceous Vegetation state from the bare sand state in the lower reattachment bar is slowed by growing season extended high flows, and growing season extended low or high flows contribute to transitions of the *Phragmites australis* Temperate Herbaceous Vegetation state to other states. The effect of differences between alternatives is greater than the effect of differences between hydrologic traces.

G.1.2.3 Native/Nonnative Ratio Metric

Relative change in the ratio of native (other than arrowweed)/nonnative dominated vegetation community types on sandbars and channel margins (change in native/nonnative ratio = ratio$_{final}$/ratio$_{initial}$).

The Native/Nonnative Ratio metric is calculated using the ratio of the cover of each of the four native-dominated states to the cover of the tamarisk state. The ratio of the final (modeled) cover is then divided by the ratio of the initial mapped cover. The results for the Native/Nonnative Ratio metric based on historical flows are shown in Figure G-5; the three highest-scoring long-term strategies, E6, E3, and E5, are not significantly different from each other (between means based on a three-factor ANOVA followed by Tukey's Studentized Range [HSD] Test); long-term strategy E5 is not significantly different from long-term strategy B1. Results under projected climate change are similar to those for historical flows (all alternatives score slightly higher) and are shown in Figure G-6; thus the performance of each alternative under climate change would be similar to that modeled under historical conditions.

Native states tend to increase with growing and non-growing seasons without extended high or low flows. The tamarisk state tends to increase with extended high flows followed by extended low flows, as well as spring HFEs with an extended low or high flow. Under Alternative C, long-term strategy C1, and Alternative F, high flows shift all states to sand, which then shifts to tamarisk (e.g., lower reattachment bar, growing season extended low).

G.1.2.4 Arrowweed Metric

Relative change in the arrowweed state on sandbars and channel margins using the total percent decrease in arrowweed states (change in arrowweed = $\text{arrowweed}_{initial}/\text{arrowweed}_{final}$). The results for the arrowweed metric based on historical flows are shown in Figure G-7; the two highest-scoring long-term strategies, C1 and C2, are not significantly different from each other (between means based on a three-factor ANOVA followed by Tukey's Studentized Range [HSD] Test); long-term strategy C2 is not significantly different from Alternatives F and G. Results under projected climate change are similar to those for historical flows (all alternatives score slightly lower) and are shown in Figure G-8; thus the performance of each alternative under climate change would be similar to that modeled under historical conditions (Alternative F would be the highest scoring, however).

To illustrate the relative change in arrowweed, acreage changes for several alternatives/long-term strategies are shown in Table G-7.

The arrowweed state tends to increase with extended high and extended low flows, but this increase can be slowed by fall HFEs. The effect of differences between hydrologic traces is greater than the effect of differences between alternatives.

G.1.2.5 Overall Score

The results for the overall score based on historical flows are shown in Figure G-9; The six highest-scoring long-term strategies, D4, E4, E6, E3, E5, and B1, are not significantly different from each other (between means based on a three-factor ANOVA followed by Tukey's Studentized Range [HSD] Test); long-term strategies E5 and B1 are not significantly different from long-term strategy E2. These alternatives included the five highest scores in the Native Cover metric and Native/Nonnative Ratio. The lowest scoring is long-term strategy C3, which is the lowest in the arrowweed metric and consistently low scoring in the other metrics. Results under projected climate change are similar to those for historical flows, with four alternatives showing a slight decrease and all others with a slight increase, and are shown in Figure G-10; thus the performance of each alternative under climate change would be similar to that modeled under historical conditions.

For the overall score, the effects of the differences between alternatives are greater than the effects of differences between hydrologic traces; sediment traces 1 and 2 are significantly different.

In reviewing the components of the overall score:

- Native Cover Index: long-term strategies E6 and E3 are the highest scoring; native states tend to increase with growing and non-growing seasons without extended high or low flows.

- Native Diversity Index: long-term strategies E4 and B1 are the highest scoring. The transition to the *Phragmites australis* Temperate Herbaceous Vegetation state from the bare sand state in the lower reattachment bar is slowed by growing season extended high flows, reducing diversity, and growing season extended low or high flows contribute to transitions of the *Phragmites australis* Temperate Herbaceous Vegetation state to other states.

- Native/Nonnative Ratio: long-term strategies E6, E3, and E5 are the highest scoring; the tamarisk state tends to increase with extended high flows followed by extended low flows, as well as spring HFEs with an extended low or high flow.

- Arrowweed Index: long-term strategies C1and C2 are the highest scoring; the arrowweed state tends to increase with extended high and extended low flows.

G.1.3 Wetlands

Two of the model states discussed above represent wetland community types: *Phragmites australis* Temperate Herbaceous Vegetation, a marsh community; and *Salix exigua-Baccharis emoryi* Shrubland/*Equisetum laevigatum* Herbaceous Vegetation, a shrub wetland community. These occur on the lower reattachment bar and lower channel margin (as well as lower reattachment bar), respectively (Table G-1), and occupy 4.4 and 0.2 ac, respectively (Table G-5). The relative change in cover of these wetland community types was calculated from the model results using the method described for metric 1 above. The results for the 19 alternatives/long-term strategies are presented in Figure G-11 (a score of 1.0 means no change from initial conditions). Only Alternative E long-term strategies E3, E5, and E6 show an increase in wetland community cover (based on mean scores); all others show a decrease. Decreases of greater than 50% occur under Alternative B, long-term strategy B2; Alternative C; Alternative F; and Alternative G. Results under projected climate change are similar to those for historical flows (all alternatives score slightly higher; however, Alternative F shows only a minimal increase), and are shown in Figure G-12; thus the performance of each alternative under climate change would be similar to that modeled under historical conditions.

G.2 ALTERNATIVE-SPECIFIC IMPACTS

This section provides additional information related to the impacts of alternatives, specifically the impacts associated with the long-term strategies that were analyzed for condition-dependent alternatives (Alternatives B, C, D, and E). This analysis supplements the information presented in Section 4.6 of the DEIS.

G.2.1 Alternative A (No Action Alternative)

Alternative A includes sediment-triggered spring and fall HFEs through 2020 (no spring HFEs until 2015). Alternative A has higher monthly volumes in the high electricity demand months of December, January, July, and August. This alternative has fewer spring and fall HFEs than other alternatives, occasional extended low flows, and more frequent extended high flows than most other alternatives, the latter being particularly frequent in the growing season. The model results for each of the metrics as well as the overall score are presented in Table G-8.

G.2.2 Alternative B

Alternative B includes spring and fall HFEs (the number of HFEs not to exceed one every other year). This alternative lacks low summer flows, and has higher monthly volumes December–January and July–August. Alternative B has few spring HFEs, similar to Alternative A, but it also has more fall HFEs than Alternative A. The expected number of HFEs would be lower under this alternative than under any other. This alternative has the same monthly pattern in release volume as the Alternative A; however, Alterative B has no extended low flows; long-term strategy B1 has a slightly greater frequency of extended high flows compared to Alternative A, and long-term strategy B2 has considerably more extended high flows than long-term strategy B1—far more than any other alternative long-term strategy. The results for this alternative are presented for long-term strategy B1 (Table G-9), followed by long-term strategy B2 (Table G-10).

G.2.3 Alternative C

Alternative C includes spring and fall HFEs in long-term strategies C1 and C2, fall HFEs only in long-term strategy C4, and no HFEs in long-term strategy C3; proactive spring HFEs are tested in April, May, or June in high-volume years. This alternative features low summer flows in some years in long-term strategy C2, and has highest monthly release volumes December–January and July, and lower volumes from August through November. Long-term strategies C1–C4 have more extended low flows and fewer growing season extended high flows than Alternative A (although long-term strategies C2–C4 have more growing season extended high flows than long-term strategy C1); long-term strategy C3 has slightly more non-growing season extended high flows than the other Alternative C long-term strategies. Long-term strategies C1 and C2 have considerably more spring and fall HFEs than Alternative A; the number of long-term strategy C4 fall HFEs is similar to those of long-term strategies C1 and C2. The model results for each of the metrics, as well as the overall score for this alternative, are presented for long-term strategy C1 (Table G-11), followed by long-term strategies C2 (Table G-12), C3 (Table G-13), and C4 (Table G-14).

G.2.4 Alternative D (Preferred Alternative)

Alternative D includes spring (March–April) and fall (October–November) HFEs; proactive spring HFEs (24 hours, 45,000 cfs) would be tested (April, May, or June) in high-volume years; no spring HFEs the first 2 years; and extended-duration fall HFEs (up to 250-hour duration, up to 45,000 cfs), up to four in a 20-year period. As a result, Alternative D has a greater frequency of fall and spring HFEs compared to the Alternative A. Monthly water volumes would be similar to Alternative E but August and September would have higher volumes and January through July would be slightly lower than Alternative E. A 2- or 3-year test for invertebrate production would reduce flows to the minimum flow for the month on Saturdays and Sundays in May through August starting the third year of the LTEMP period; if successful, these flows would be implemented for the remainder of the LTEMP period (up to 18 years total), resulting in few, if any, growing season extended high flows during those years. Low summer flows (July, August, September) would be tested in two or three of the second 10 years. This alternative has very few growing season extended low flows, as well as slightly fewer non-growing season extended low or high flows, due to the monthly pattern of flows as well as the amount of daily fluctuations. Alternative D has frequent growing season extended high flows but not as many as under Alternative A. Seasons, especially non-growing seasons, without extended low or high flows are frequent. The model results for each of the metrics as well as the overall score for this alternative are presented for long-term strategy D1 (Table G-15) followed by long-term strategies D2 (Table G-16), D3 (Table G-17), and D4 (Table G-18).

G.2.5 Alternative E

Alternative E includes spring and fall HFEs; no spring HFEs in first 10 years; rapid response is tested every fourth HFE matching Paria flood; spring and fall HFEs in long-term strategies E1 and E2; fall HFEs only in long-term strategy E4; and no HFEs in long-term strategies E3, E5, and E6. This alternative has lower monthly water volumes in August, September, and October. Low summer flows occur in some years (triggered) of the second 10 years in long-term strategies E2 and E5. Long-term strategies E1–E6 have fewer growing season extended high flows than Alternative A, (long-term strategies E2 and E5 have slightly more than the other Alternative E long-term strategies); and more HFEs than Alternative A. Long-term strategies E1 and E2 have similar numbers of HFEs; the number of long-term strategy E4 fall HFEs is similar to long-term strategies E1 and E2. The model results for each of the metrics as well as the overall score for this alternative are presented for long-term strategy E1 (Table G-19), followed by long-term strategies E2 (Table G-20), E3 (Table G-21), E4 (Table G-22), E5 (Table G-23), and E6 (Table G-24).

G.2.6 Alternative F

Alternative F includes spring and fall HFEs; peak flows in May and June; base flows from July through January; and a 168-hour (7-day) 25,000 cfs flow at the end of June. This alternative also features higher volumes than Alternative A April–June, and lower volumes than Alternative A in the other months. This alternative has more extended low flows, slightly fewer extended high flows, and considerably more HFEs than Alternative A (more than any other alternative). The model results for each of the metrics as well as the overall score for this alternative are presented in Table G-25.

G.2.7 Alternative G

Alternative G includes spring and fall HFEs; HFEs can extend for up to 336 hours (2 weeks); proactive spring HFEs are tested in high-volume years; and monthly volumes vary only in response to runoff forecast and other requirements. This alternative has more extended low flows and fewer extended high flows than Alternative A. The model results for each of the metrics, as well as the overall score for this alternative, are presented in Table G-26.

G.3 SUMMARY

Transitions between plant community types, or to bare sand, are driven by specific flow events that vary among the alternatives. Spring HFEs, fall HFEs, spill flows, extended low flows, extended high flows, and seasons without extended high or low flows occurring during the growing or non-growing season result in changes in the distribution and cover of New High Water Zone plant communities.

HFEs result in sediment deposition, but scouring is minor and limited to low-elevation wetland species. HFEs transport seeds of nonnative as well as native species. Repeated extended high flows result in removal of vegetation by drowning and scouring, primarily on lower elevation surfaces. Increased soil moisture at upper elevations from extended high flows can increase vegetation growth and seedling establishment. The germination of seeds transported by HFEs or extended high flows is promoted by extended low flows (e.g., elevated base flows) that reduce disturbance, expose lower elevation surfaces, and maintain soil moisture at lower elevations, all of which are conducive to seedling growth. Extended low flows also can result in the lowering of groundwater levels, thus increasing the depth to groundwater and the reduction of soil moisture, creating conditions that favor the growth of more drought-tolerant species.

Repeated seasons of extended high flows, extended high flows above 50,000 cfs, or spill flows transition native communities to bare sand through the processes of drowning, scouring, and burial. All the alternatives would result in a decrease in native plant community cover. Wetland communities generally transition only from bare sand or other wetlands; they can transition back to bare sand or to arrowweed, tamarisk, or cottonwood-willow communities. Alternatives that include frequent extended low flows, such as annually for Alternative F, or extended high flows followed by extended low flows tend to result in transitions of wetlands to other plant community types. All the alternatives are expected to result in a decrease in wetland cover, with particularly large decreases for Alternative F.

The overall cover of tamarisk-dominated communities would be expected to increase under Alternatives C, F, and G, each of which is expected to produce frequent transitions to tamarisk communities, in large part because they frequently have extended high flows, extended low flows, and spring HFEs. This combination of flows encourages transitions to tamarisk because tamarisk increases when high flows coincide with seed release during spring and early summer, followed by lower flows, all of which results in establishment of seedlings above the elevation of subsequent floods. Also, under these alternatives, various community types frequently shift to bare sand, which then shifts to tamarisk. Each of these alternatives has more extended low flows and more spring HFEs than the other alternatives. The overall cover of the tamarisk is expected to decrease under Alternatives A, B, D, and E. Each of these alternatives has frequent extended high flows, which result in consecutive seasons and consecutive years of extended high flows. Two or more years of extended high flows are required for tamarisk to be removed by drowning, leaving a bare sand lower reattachment bar, or two consecutive seasons on a lower separation bar.

The overall cover of the arrowweed community would be expected to increase under Alternatives A, B, and E; under these alternatives, bare sand would transition to arrowweed rather than tamarisk because there are few spring HFEs and/or few growing-season extended high flows, both of which promote the establishment of tamarisk on bare sand, and, except in Alternative B, arrowweed would transition from marsh because of growing-season extended low flows. Once established, arrowweed would tend to remain for many years under these alternatives. HFEs alone are not effective at reducing arrowweed as burial typically results in resprouting from roots, buried stems, and rhizomes, and subsequent vegetative growth occurs. Arrowweed would decrease under Alternatives C, D, F, and G, usually by transitioning to bare sand with repeated extended high flows, but often by transitioning to tamarisk.

G.4 REFERENCES

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TABLE G-1 Vegetation States, Plant Associations, and Corresponding Submodels

Vegetation States	Primary Plant Species	Additional Species	Submodel/Landform
Bare Sand	<1% vegetation		All submodels
Phragmites australis Temperate Herbaceous Vegetation[a]	Common reed (*Phragmites australis*), cattail (*Typha domingensis*, *T. latifolia*)	Common tule (*Schoenoplectus acutus*), creeping bent grass (*Agrostis stolonifera*)	Lower Reattachment Bar
Salix exigua–Baccharis emoryi Shrubland/ *Equisetum laevigatum* Herbaceous Vegetation[a]	Horsetail (*Equisetum laevigatum*), coyote willow (*Salix exigua*), *Baccharis emoryi*, *Schoenoplectus pungens*	*Eleocharis palustris, Muhlenbergia asperifolia*	Lower Channel Margin, Lower Reattachment Bar
Tamarix spp. Temporarily Flooded Shrubland[b]	Tamarisk (*Tamarix* spp.)		All submodels
Populus fremontii/Salix exigua Forest[a]	Coyote willow, cottonwood (*Populus fremontii*)	*Salix gooddingii, Baccharis salicifolia, Distichlis spicata, Muhlenbergia asperifolia, Phragmites australis*, *Equisetum* spp., *Juncus spp.*, *Carex* spp., *Elaeagnus angustifolia, Tamarix* spp., *Poa pratensis, Melilotus* spp.	Lower Channel Margin, Lower Separation Bar
Pluchea sericea Seasonally Flooded Shrubland	Arrowweed (*Pluchea sericea*)	*Baccharis* spp., *Mesquite* (*Prosopis glandulosa*), coyote willow	Lower Reattachment Bar, Upper Separation Bar, Upper Reattachment Bar, Upper Channel Margin
Prosopis glandulosa var. *torreyana* Shrubland[a]	Mesquite (*Prosopis glandulosa* var. *torreyana*)	*Baccharis* spp., *Pluchea sericea*,	Lower Channel Margin, Upper Separation Bar, Upper Reattachment Bar, Upper Channel Margin

[a] Native-dominated states used in the metric calculations.

[b] Nonnative-dominated state used in the metric calculations.

Source: Ralston et al. (2014).

TABLE G-2 Hydrologic Events Considered in the Riparian Vegetation Model

Event	Flow Range	Timing
Spill flow[a]	>45,000 cfs one day or more	Any month
Spring HFE	>31,500 cfs to ≤45,000 cfs, less than 30 days[b]	March–June
Fall HFE	>31,500 cfs to ≤45,000 cfs, less than 30 days[b]	October–December
Extended low flow	≤10,000 cfs for at least 30 consecutive days	Growing season; non-growing season
Extended high flow	≥20,000 cfs to ≤45,000 cfs for at least 30 consecutive days	Growing season; non-growing season
Growing or non-growing seasons without extended high or low flows	Flows that can fluctuate up to 25,000 cfs (i.e., the absence of spill flows or extended high or extended low flows)	Growing season; non-growing season

[a] Spill flows (i.e., flows that include releases through the spillway, and total >45,000 cfs) are not a function of the alternatives, but rather a function of annual hydrology. These do not differ among the alternatives.

[b] A peak or spike in flow between 31,500 cfs and 45,000 cfs that begins or ends below 31,500 cfs is considered an HFE.

TABLE G-3 Riparian Vegetation Model Transition Rules

Transition	From	To	Trigger	Notes
Upper Separation Bar				
T1	Bare Sand	*Pluchea sericea* Seasonally Flooded Shrubland	*Pluchea* cover[a] = 30%	*Pluchea* growth variable (before T1 transition): cover starts at 1% in bare sand frame; non-growing season extended low flow or season without extended high or low flow + growing season extended low flow or season without extended high or low flow same year = 5%; non-growing season extended low flow or season without extended high or low flow + growing season extended high flow same year = 7.5%; non-growing season extended high flow + growing season extended low flow or season without extended high or low flow same year = 7.5%; non-growing season extended high flow + growing season extended high flow same year = 10%; fall HFE same year = increase × 0.5
T2	Bare Sand	Tamarisk Temporarily Flooded Shrubland	Spring HFE + growing season extended high flow same year	*Pluchea* cover must be ≤10%
T3	Tamarisk Temporarily Flooded Shrubland	*Prosopis glandulosa* var. torreyana Shrubland	*Prosopis* cover = 25%	*Prosopis* growth variable (before T3 transition): cover starts at 0% in tamarisk frame; spring HFE + growing season without extended high or low flow same year = +2%; spring HFE + growing season extended high flow same year = +2%; growing season extended low flow = -0.5%
T4	Tamarisk Temporarily Flooded Shrubland, *Pluchea sericea* Seasonally Flooded Shrubland, or *Prosopis glandulosa* var. *torreyana* Shrubland	Bare Sand	Spill flow; <u>OR</u> any season extended high flow > 50K cfs	Extended high flow must be >50K cfs

TABLE G-3 (Cont.)

Transition	From	To	Trigger	Notes
Lower Separation Bar				
T1	Bare Sand	*Populus fremontii/Salix exigua* forest	*Populus/Salix* cover = 20%	*Populus/Salix* growth variable (before T1 transition): cover starts at 1% in S1 frame; non-growing season without extended high or low flow + growing season without extended high or low flow same year = +3%; non-growing season extended high flow + growing season without extended high or low flow same year = cover × 0.5
T2	Bare Sand	Tamarisk Temporarily Flooded Shrubland	Non-growing season extended high flow + growing season extended low flow same year; <u>OR</u> spring HFE + growing season extended low flow same year	
T3	Tamarisk Temporarily Flooded Shrubland or *Populus fremontii*/*Salix exigua* Forest	Bare Sand	Non-growing season or growing season spill flow; <u>OR</u> non-growing season extended high flow + growing season extended high flow same year; <u>OR</u> growing season extended high flow + non-growing season extended high flow next year	
Lower Reattachment Bar				
T1	Bare Sand	*Phragmites australis* Temperate Herbaceous Vegetation	*Phragmites* cover = 20%	*Phragmites* growth variable (before T1 transition): growing season without extended high or low flow = +10%; growing season extended high flow set to 0

TABLE G-3 (Cont.)

Transition	From	To	Trigger	Notes
Lower Reattachment Bar (Cont.)				
T2	*Phragmites australis* Temperate Herbaceous Vegetation	*Salix exigua-Baccharis emoryi* shrubland/*Equisetum laevigatum* Herbaceous Vegetation	Growth variable = 4 (see "Notes" column of this table for growth variable calculation)	*Salix-Baccharis/Equisetum* growth variable (before T2 transition): non-growing season without extended high or low flow + growing season without extended high or low flow same year = +1; fall HFE or spring HFE = -1; any season extended high flow sets to 0. Values are not additive within a year; e.g., fall HFE + spring HFE in same year is still -1. Non-growing season extended low flow = season without extended high or low flow.
T3	*Salix exigua-Baccharis emoryi* Shrubland/*Equisetum laevigatum* Herbaceous Vegetation	Tamarisk Temporarily Flooded Shrubland	Non-growing season extended high flow + growing season extended low flow same year; <u>OR</u> growing season extended high flow + next year growing season extended low flow	
T4	*Phragmites australis* Temperate Herbaceous Vegetation, or *Salix exigua-Baccharis emoryi* Shrubland/*Equisetum laevigatum* Herbaceous Vegetation, or *Pluchea sericea* Seasonally Flooded Shrubland	Bare Sand	Non-growing season extended high flow + growing season extended high flow same year; <u>OR</u> growing season extended high flow + non-growing season extended high flow next year; <u>OR</u> growing season extended high flow + growing season extended high flow next year; <u>OR</u> any spill flow	
T5	*Phragmites australis* Temperate Herbaceous Vegetation	Tamarisk Temporarily Flooded Shrubland	Non-growing season extended high flow + growing season extended low flow same year <u>OR</u> growing season extended high flow + growing season extended low flow next year	

TABLE G-3 (Cont.)

Transition	From	To	Trigger	Notes
Lower Reattachment Bar (Cont.)				
T6	Tamarisk Temporarily Flooded Shrubland	Bare Sand	Growing season extended high flow + non-growing season extended high flow in sequence of 4; OR growing season extended high flow in sequence of 4; OR any season spill flow	Does not have to be same year
T7	Bare Sand	Tamarisk Temporarily Flooded Shrubland	Growing season extended low flow	
T8	*Pluchea sericea* Seasonally Flooded Shrubland	Tamarisk Temporarily Flooded Shrubland	Growing season extended high flow + growing season extended low flow the next year OR non-growing season extended high flow + growing season extended low flow same year	
T9	*Phragmites australis* Temperate Herbaceous Vegetation	*Pluchea sericea* Seasonally Flooded Shrubland	Growing season extended low flow	NOT if non-growing season extended high flow same year (then *Phragmites* transitions to tamarisk).
Lower Channel Margin				
T1	Bare Sand	*Salix exigua-Baccharis emoryi* Shrubland/*Equisetum laevigatum* Herbaceous Vegetation	Growth variable = 4 (see *Notes* for growth variable calculation)	*Salix-Baccharis/Equisetum* growth variable (before T1 transition): non-growing season without extended high or low flow + growing season without extended high or low flow same year = +1; growing season extended low flow = -1; fall HFE or spring HFE = -1; any season extended high flow sets to 0. Values are not additive within a year; e.g., fall HFE + growing season extended low flow in same year is still -1.

TABLE G-3 (Cont.)

Transition	From	To	Trigger	Notes
Lower Channel Margin (Cont.)				
T2	*Salix exigua-Baccharis emoryi* Shrubland/*Equisetum laevigatum* Herbaceous Vegetation	*Populus fremontii/Salix exigua* Forest	Non-growing season extended high flow + growing season extended low flow same year; OR growing season extended high flow + next year growing season extended low flow	
T3	Bare Sand	Tamarisk Temporarily Flooded Shrubland	Non-growing season extended high flow + growing season extended low flow	*Salix-Baccharis/Equisetum* must be ≤2.
T4	Tamarisk Temporarily Flooded Shrubland	*Prosopis glandulosa* var. *torreyana Shrubland*	*Prosopis* cover = 25%	*Prosopis* growth variable (before T4 transition): cover starts at 0% in woody riparian tamarisk frame; spring HFE + growing season without extended high or low flow same year = 2%; spring HFE + growing season extended high flow = 2%; growing season extended low flow = -0.5%
T5	Tamarisk Temporarily Flooded Shrubland, *Populus fremontii/Salix exigua* Forest, *Prosopis glandulosa* var. *torreyana* Shrubland	Bare Sand	Any season spill flow; OR any season extended high flow >50K cfs	Extended high flow must be >50K cfs
T6	*Salix exigua-Baccharis emoryi* Shrubland/*Equisetum laevigatum* Herbaceous Vegetation	Bare Sand	Any season extended high flow >25K cfs	Extended high flow must be >25K cfs

[a] Percent cover refers to the overall percentage of a hypothetical geomorphic feature (e.g., lower reattachment bar) beneath a vertical projection of the vegetation canopy.

1

TABLE G-4 New High-Water Zone and Old High-Water Zone Vegetation Classes Mapped from Lees Ferry to Diamond Creek[a]

Vegetation Class	Dominant Species	Area (ac)
New High-Water Zone		
Phragmites australis Western North America Temperate Semi-natural Herbaceous Vegetation	Cattail, common reed	4.4
Tamarix spp. Temporarily Flooded Semi-natural Shrubland	Tamarisk	273.7
Baccharis spp.–*Salix exigua*–*Pluchea sericea* Shrubland Alliance	*Baccharis* spp., coyote willow, arrowweed	354.7
Prosopis glandulosa var. *torreyana* Shrubland	Western honey mesquite	137.1
Abronia elliptica Herbaceous Dune Vegetation	Fragrant white sand verbena	4.0
Acacia greggii Shrubland	Catclaw acacia	30.4
Arctostaphylos–*Quercus turbinella* Shrubland Alliance	Bearberry, live oak	2.2
Artemisia bigelovii Shrubland Alliance	Bigelow sagebrush	1.1
Artemisia tridentata Shrubland Alliance	Big sagebrush	2.4
Brickellia longifolia–*Fallugia paradoxa*–*Isocoma acradenia* Shrubland	Longleaf brickellbush, Apache plume, goldenbush	65.5
Encelia (*farinosa, resinifera*) Shrubland Alliance	Brittlebush, sticky brittlebush	401.0
Ephedra (*torreyana, viridis*) Mixed Semi-desert Grasses Shrubland	Mormon tea, green ephedra	29.0
Ephedra fasciculate Mojave Desert Shrubland Alliance	Arizona joint-fir	103.6
Ephedra torreyana–*Opuntia basilaris* Shrubland	Mormon tea, beavertail cactus	64.0
Gutierrezia (*sarothrae, microcephala*)–*Ephedra* (*torreyana, viridis*) Mojave Desert Shrubland Alliance	Snakeweed, broom snakeweed, Mormon tea, green ephedra	14.5
Larrea tridentata–*Encelia* spp. Shrubland Alliance	Creosote, brittlebush	15.3
Sparsely Vegetated Slickrock	–[b]	5.4
Other[c]	–	5.0

TABLE G-4 (Cont.)

Vegetation Class	Dominant Species	Area (ac)
Old High-Water Zone		
Abronia elliptica Herbaceous Dune Vegetation	Fragrant white sand verbena	5.7
Acacia greggii Shrubland	Catclaw acacia	56.1
Artemisia tridentata Shrubland Alliance	Big sagebrush	1.1
Baccharis spp.–*Salix exigua–Pluchea sericea* Shrubland Alliance	*Baccharis* spp., coyote willow, arrowweed	200.2
Brickellia longifolia–Fallugia paradoxa–Isocoma acradenia Shrubland	Longleaf brickellbush, Apache plume, goldenbush	78.5
Encelia (*farinosa, resinifera*) Shrubland Alliance	Brittlebush, sticky brittlebush	438.1
Ephedra (*torreyana, viridis*) Mixed Semi-desert Grasses Shrubland	Mormon tea, green ephedra	41.4
Ephedra fasciculata Mojave Desert Shrubland Alliance	Arizona joint-fir	120.1
Ephedra torreyana–(*Atriplex canescens, Atriplex confertifolia*) Sparse Vegetation	Mormon tea, four-wing saltbush, shadscale	2.1
Ephedra torreyana–Opuntia basilaris Shrubland	Mormon tea, beavertail cactus	109.7
Great Basin and Intermountain Ruderal Dry Shrubland and Grassland Group	–	1.1
Gutierrezia (*sarothrae, microcephala*)–*Ephedra* (*torreyana, viridis*) Mojave Desert Shrubland Alliance	Snakeweed, broom snakeweed, Mormon tea, green ephedra	24.0
Larrea tridentata–Encelia spp. Shrubland Alliance	Creosote, brittlebush	41.4
Pleuraphis rigida Herbaceous Vegetation	Big galleta	1.3
Prosopis glandulosa var. *torreyana* Shrubland	Western honey mesquite	315.9
Sparsely Vegetated Slickrock	–	1.4
Tamarix spp. Temporarily Flooded Semi-natural Shrubland	Tamarisk	224.6
Unvegetated Surfaces and Built-up Areas	–	32.1
Other[c]	–	6.4

Footnotes on next page.

TABLE G-4 (Cont.)

[a] The New High-Water Zone and Old High-Water Zone were separated at the 45,000 cfs stage elevation.

[b] – = No dominant species identified.

[c] Includes all vegetation classes with less than 1 ac mapped within the zone.

Source: Kearsley et al. (2015).

TABLE G-5 Vegetation States and Corresponding Mapped Vegetation Types

Vegetation States	Mapped Vegetation Classes[a]	Area (acres)
Bare Sand	Unvegetated Surfaces and Built Up Areas	112
Phragmites australis Temperate Herbaceous Vegetation	*Phragmites australis* Western North America Temperate Semi-natural Herbaceous Vegetation	4.4
Salix exigua Baccharis emoryi shrubland/*Equisetum laevigatum* Herbaceous Vegetation	Arid West Emergent Marsh	0.2
Tamarisk Temporarily Flooded Shrubland	*Tamarix* spp. Temporarily Flooded Semi-natural Shrubland	273.7
Populus fremontii/Salix exigua Forest	*Baccharis* spp.–*Salix exigua–Pluchea sericea* Shrubland Alliance	177.3[b]
Pluchea sericea Seasonally Flooded Shrubland	*Baccharis* spp.–*Salix exigua–Pluchea sericea* Shrubland Alliance	177.3[b]
Prosopis glandulosa var. *torreyana* Shrubland	*Prosopis glandulosa* var. *torreyana Shrubland*	137.1

[a] Kearsley et al. (2015), which mapped river miles 0–278; vegetation classes and area are based on 2007 and 2010 aerial photography and do not necessarily reflect current conditions.

[b] The *Baccharis* spp.–*Salix exigua–Pluchea sericea* Shrubland Alliance (354.7 ac) was divided equally between the *Populus fremontii/Salix exigua* forest state and *Pluchea sericea* Seasonally Flooded Shrubland state.

TABLE G-6 Example Results for the Native Cover Metric[a]

Alternative/ Long-Term Strategy	Final Acres	Change
E6	307	−12
D4	280	−39
A	264	−55
B2	169	−150

[a] Initial acres: 319 (based on Kearsley et al. 2015).

TABLE G-7 Example Results for the Arrowweed Metric[a]

Alternative/ Long-Term Strategy	Final Acres	Change
C1, C2	152	−25
D4	160	−17
A	222	45
C3	235	58

[a] Initial acres: 177 (based on Kearsley et al. 2015).

TABLE G-8 Results for Alternative A

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.827	0.983	1.051	0.799	3.661
Change	17.3% reduction in cover of native states	1.7% reduction in diversity of native states[a]	5.1% increase in the native/ nonnative ratio	25.1% increase in the arrowweed state cover	Overall movement away from the resource goal
Modeled values	263.8 ac, all four native states (initial cover 319.0 ac)	Modeled diversity 1.065, all four native states (initial diversity 1.083)	Modeled ratio 1.226 (initial ratio 1.166)	221.8 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 55.2 ac	NA	Tamarisk state decrease of 58.4 ac[b]	Arrowweed state increase of 44.5 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

TABLE G-9 Results for Alternative B, Long-Term Strategy B1

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.849	1.027	1.148	0.842	3.865
Change	15.1% reduction in cover of native states	2.7% increase in diversity of native states[a]	14.8% increase in the native/ nonnative ratio	18.8% increase in the arrowweed state cover	Movement away from the resource goal
Modeled values	270.7 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.113, all four native states (initial diversity 1.083)	Modeled ratio 1.338 (initial ratio 1.166)	210.6 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 48.3 ac	NA	Tamarisk state decrease of 71.4 ac[b]	Arrowweed state increase of 33.3 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

TABLE G-10 Results for Alternative B, Long-Term Strategy B2

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0. 529	0.913	0. 869	0. 809	3.120
Change	47.1% reduction in cover of native states	8.7% decrease in diversity of native states[a]	13.1% decrease in the native/ nonnative ratio	23.6% increase in the arrowweed state cover	Movement away from the resource goal
Modeled values	168.9 ac, all four native states (initial cover 319 ac)	Modeled diversity 0.988, all four native states (initial diversity 1.083)	Modeled ratio 1.013 (initial ratio 1.166)	219.2 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 150.1 ac	NA	Tamarisk state decrease of 107.0 ac[b]	Arrowweed state increase of 41.9 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

TABLE G-11 Results for Alternative C, Long-Term Strategy C1

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.631	0.924	0.457	1.165	3.177
Change	36.9% reduction in cover of native states	7.6% decrease in diversity of native states[a]	54.3% decrease in the native/ nonnative ratio	14.2% decrease in the arrowweed state cover	Movement away from the resource goal
Modeled values	201.3 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.001, all four native states (initial diversity 1.083)	Modeled ratio 0.533 (initial ratio 1.166)	152.2 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 117.7 ac	NA	Tamarisk state increase of 104.0 ac[b]	Arrowweed state decrease of 25.1 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

TABLE G-12 Results for Alternative C, Long-Term Strategy C2

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.632	0.925	0.463	1.163	3.183
Change	36.8% reduction in cover of native states	7.5% decrease in diversity of native states[a]	53.7% decrease in the native/ nonnative ratio	14.0% decrease in the arrowweed state cover	Movement away from the resource goal
Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Modeled values	201.5 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.001, all four native states (initial diversity 1.083)	Modeled ratio 0.540 (initial ratio 1.166)	152.4 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 117.5 ac	NA	Tamarisk state increase of 99.3 ac[b]	Arrowweed state decrease of 24.9 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

TABLE G-13 Results for Alternative C, Long-Term Strategy C3

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.626	0.923	0.529	0.755	2.834
Change	37.4% reduction in cover of native states	7.7% decrease in diversity of native states[a]	47.1% decrease in the native/ nonnative ratio	32.5% increase in the arrowweed state cover	Movement away from the resource goal
Modeled values	199.8 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.000, all four native states (initial diversity 1.083)	Modeled ratio 0.617 (initial ratio 1.166)	234.9 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 119.2 ac	NA	Tamarisk state increase of 50.1 ac[b]	Arrowweed state increase of 57.6 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

1 **TABLE G-14 Results for Alternative C, Long-Term Strategy C4**

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.632	0.925	0.533	0.892	2.981
Change	36.8% reduction in cover of native states	7.5% decrease in diversity of native states[a]	46.7% decrease in the native/ nonnative ratio	12.1% increase in the arrowweed state cover	Movement away from the resource goal
Modeled values	201.5 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.001, all four native states (initial diversity 1.083)	Modeled ratio 0.621 (initial ratio 1.166)	198.8 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 117.5 ac	NA	Tamarisk state increase of 50.9 ac[b]	Arrowweed state increase of 21.5 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

TABLE G-15 Results for Alternative D, Long-Term Strategy D1

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.840	1.017	0.910	0.905	3.671
Change	16.0% reduction in cover of native states	1.7% increase in diversity of native states[a]	9.0% decrease in the native/ nonnative ratio	10.5% increase in the arrowweed state cover	Movement away from the resource goal
Modeled values	267.8 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.101, all four native states (initial diversity 1.083)	Modeled ratio 1.061 (initial ratio 1.166)	196.0 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 51.2 ac	NA	Tamarisk state decrease of 21.2 ac[b]	Arrowweed state increase of 18.7 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

1 **TABLE G-16 Results for Alternative D, Long-Term Strategy D2**

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.845	1.019	0.919	0.903	3.686
Change	15.5% reduction in cover of native states	1.9% increase in diversity of native states[a]	8.1% decrease in the native/ nonnative ratio	10.7% increase in the arrowweed state cover	Movement away from the resource goal
Modeled values	269.5 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.103, all four native states (initial diversity 1.083)	Modeled ratio 1.072 (initial ratio 1.166)	196.2 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 49.5 ac	NA	Tamarisk state decrease of 22.2 ac[b]	Arrowweed state increase of 18.9 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

1 **TABLE G-17 Results for Alternative D, Long-Term Strategy D3**

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.859	1.019	0.930	0.889	3.697
Change	14.1% reduction in cover of native states	1.9% increase in diversity of native states[a]	7.0% decrease in the native/ nonnative ratio	12.5% increase in the arrowweed state cover	Movement away from the resource goal
Modeled values	274.0 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.104, all four native states (initial diversity 1.083)	Modeled ratio 1.084 (initial ratio 1.166)	199.5 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 45.0 ac	NA	Tamarisk state decrease of 21.0 ac[b]	Arrowweed state increase of 22.2 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

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TABLE G-18 Results for Alternative D, Long-Term Strategy D4

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.876	1.017	0.954	1.107	3.954
Change	12.4% reduction in cover of native states	1.7% increase in diversity of native states[a]	4.6% decrease in the native/ nonnative ratio	9.6% decrease in the arrowweed state cover	Movement away from the resource goal
Modeled values	279.5 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.101, all four native states (initial diversity 1.083)	Modeled ratio 1.112 (initial ratio 1.166)	160.2 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 39.5 ac	NA	Tamarisk state decrease of 22.4 ac[b]	Arrowweed state decrease of 17.1 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

TABLE G-19 Results for Alternative E, Long-Term Strategy E1

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.801	0.979	0.961	0.801	3.541
Change	19.9% reduction in cover of native states	2.1% decrease in diversity of native states[a]	3.9% decrease in the native/ nonnative ratio	24.8% increase in the arrowweed state cover	Movement away from the resource goal
Modeled values	255.5 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.060, all four native states (initial diversity 1.083)	Modeled ratio 1.120 (initial ratio 1.166)	221.3 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 63.5 ac	NA	Tamarisk state decrease of 45.7 ac[b]	Arrowweed state increase of 44.0 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

TABLE G-20 Results for Alternative E, Long-Term Strategy E2

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.875	1.019	1.067	0.881	3.842
Change	12.5% reduction in cover of native states	1.9% increase in diversity of native states[a]	6.7% increase in the native/ nonnative ratio	13.5% increase in the arrowweed state cover	Movement away from the resource goal
Modeled values	279.3 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.103, all four native states (initial diversity 1.083)	Modeled ratio 1.244 (initial ratio 1.166)	201.2 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 39.7 ac	NA	Tamarisk state decrease of 49.2 ac[b]	Arrowweed state increase of 23.9 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

TABLE G-21 Results for Alternative E, Long-Term Strategy E3

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.961	0.977	1.227	0.768	3.932
Change	3.9% reduction in cover of native states	2.3% decrease in diversity of native states[a]	22.7% increase in the native/ nonnative ratio	30.3% increase in the arrowweed state cover	Movement away from the resource goal
Modeled values	306.5 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.058, all four native states (initial diversity 1.083)	Modeled ratio 1.430 (initial ratio 1.166)	231.0 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 12.5 ac	NA	Tamarisk state decrease of 59.4 ac[b]	Arrowweed state increase of 53.7 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

TABLE G-22 Results for Alternative E, Long-Term Strategy E4

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.899	1.027	1.124	0.884	3.934
Change	10.1% reduction in cover of native states	2.7% increase in diversity of native states[a]	12.4% increase in the native/ nonnative ratio	13.2% increase in the arrowweed state cover	Movement away from the resource goal
Modeled values	286.8 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.113, all four native states (initial diversity 1.083)	Modeled ratio 1.311 (initial ratio 1.166)	200.6 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 32.2 ac	NA	Tamarisk state decrease of 54.9 ac[b]	Arrowweed state increase of 23.3 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

TABLE G-23 Results for Alternative E, Long-Term Strategy E5

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.941	0.977	1.187	0.769	3.875
Change	5.9% reduction in cover of native states	2.3% decrease in diversity of native states[a]	18.7% increase in the native/ nonnative ratio	30.0% increase in the arrowweed state cover	Movement away from the resource goal
Modeled values	300.2 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.058, all four native states (initial diversity 1.083)	Modeled ratio 1.384 (initial ratio 1.166)	230.5 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 18.8 ac	NA	Tamarisk state decrease of 56.9 ac[b]	Arrowweed state increase of 53.2 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

TABLE G-24 Results for Alternative E, Long-Term Strategy E6

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.961	0.977	1.227	0.768	3.933
Change	3.9% reduction in cover of native states	2.3% decrease in diversity of native states[a]	22.7% increase in the native/ nonnative ratio	30.3% increase in the arrowweed state cover	Movement away from the resource goal
Modeled values	306.7 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.058, all four native states (initial diversity 1.083)	Modeled ratio 1.431 (initial ratio 1.166)	231.0 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 12.3 ac	NA	Tamarisk state decrease of 59.4 ac[b]	Arrowweed state increase of 53.7 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

TABLE G-25 Results for Alternative F

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.702	0.909	0.381	1.143	3.136
Change	29.8% reduction in cover of native states	9.1% decrease in diversity of native states[a]	61.9% decrease in the native/ nonnative ratio	12.5% decrease in the arrowweed state cover	Movement away from the resource goal
Modeled values	224.0 ac, all four native states (initial cover 319 ac)	Modeled diversity 0.985, all four native states (initial diversity 1.083)	modeled ratio 0.444 (initial ratio 1.166)	155.1 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 95.0 ac	NA	Tamarisk state increase of 230.7 ac[b]	Arrowweed state decrease of 22.2 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

TABLE G-26 Results for Alternative G

Parameter	Metric 1: Change in Native Cover, Final Cover/ Initial Cover	Metric 2: Change in Diversity, Final Diversity/ Initial Diversity	Metric 3: Change in Native/ Nonnative Ratio, Final Ratio/ Initial Ratio	Metric 4: Change in Arrowweed, Initial Arrowweed/ Final Arrowweed	Overall Score
Mean score (weighted mean for all sediment traces)	0.706	0.967	0.604	1.128	3.405
Change	29.4% reduction in cover of native states	3.3% decrease in diversity of native states[a]	39.6% decrease in the native/ nonnative ratio	11.3% decrease in the arrowweed state cover	Movement away from the resource goal
Modeled values	225.3 ac, all four native states (initial cover 319 ac)	Modeled diversity 1.047, all four native states (initial diversity 1.083)	Modeled ratio 0.704 (initial ratio 1.166)	157.2 ac arrowweed state (initial cover 177.3 ac)	NA
Change in cover (acres)	Native states decrease of 93.7 ac	NA	Tamarisk state increase of 46.4 ac[b]	Arrowweed state decrease of 20.1 ac	NA

[a] Because the results for each modeled run include the same number of states (each state is a different starting condition for model runs), a reduction in diversity indicates a reduction in evenness among the vegetation states.

[b] A relative increase in native cover or decrease in nonnative cover can increase the ratio.

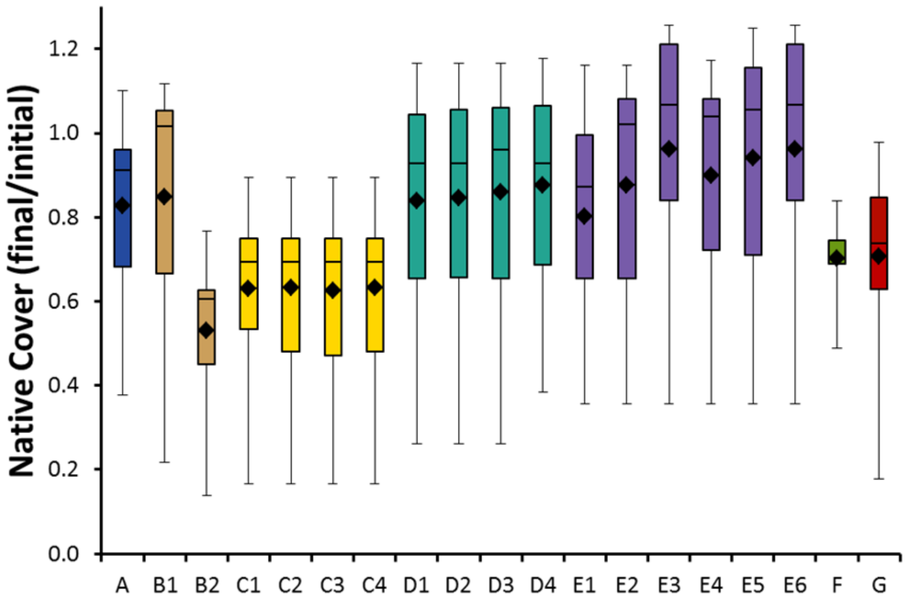

FIGURE G-1 Native Cover Metric for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers) (Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum of the values for the 63 traces analyzed.)

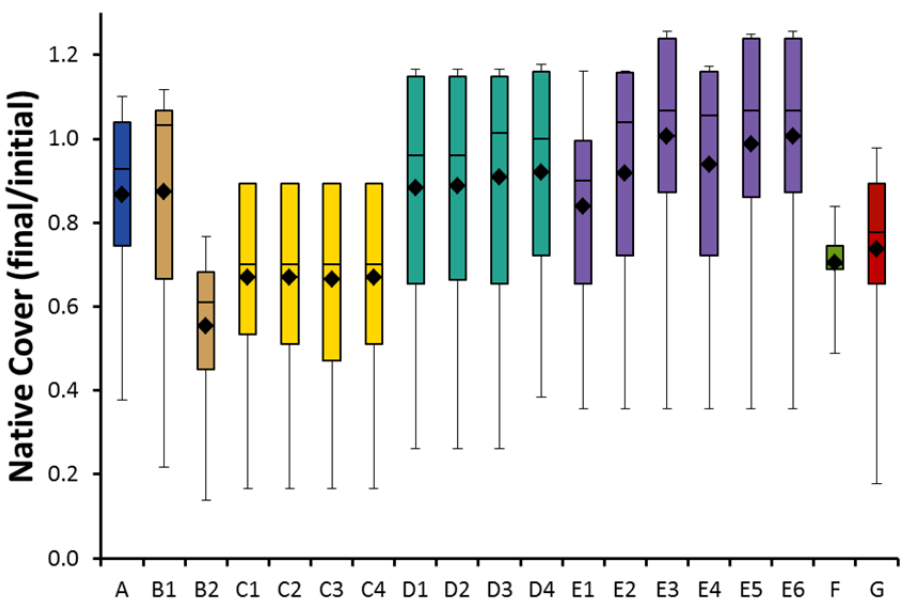

FIGURE G-2 Native Cover Metric under Climate Change for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers) (Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum of the values for the 63 traces analyzed.)

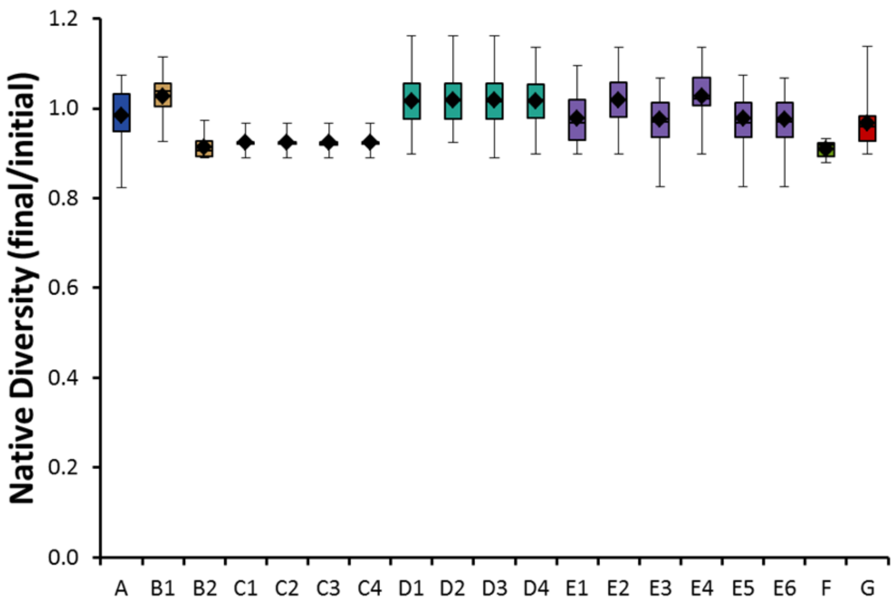

FIGURE G-3 Native Diversity Metric for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers) (Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum of the values for the 63 traces analyzed.)

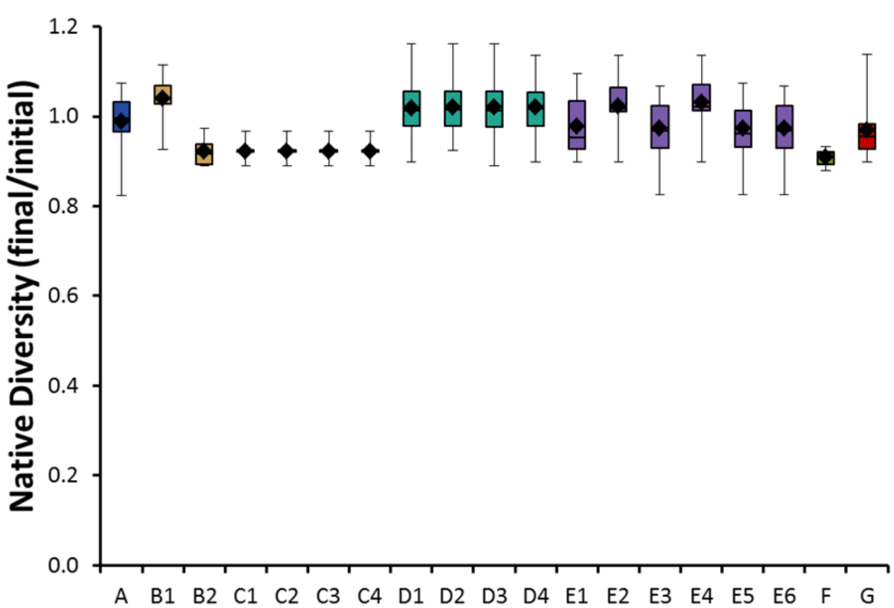

FIGURE G-4 Native Diversity Metric under Climate Change for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers) (Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum of the values for the 63 traces analyzed.)

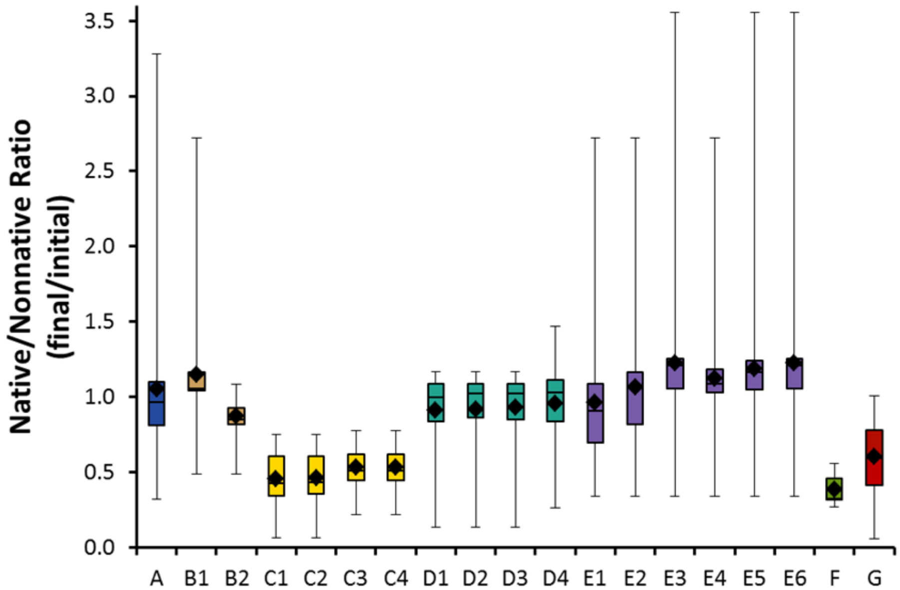

FIGURE G-5 Native/Nonnative Ratio Metric for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers) (Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum of the values for the 63 traces analyzed.)

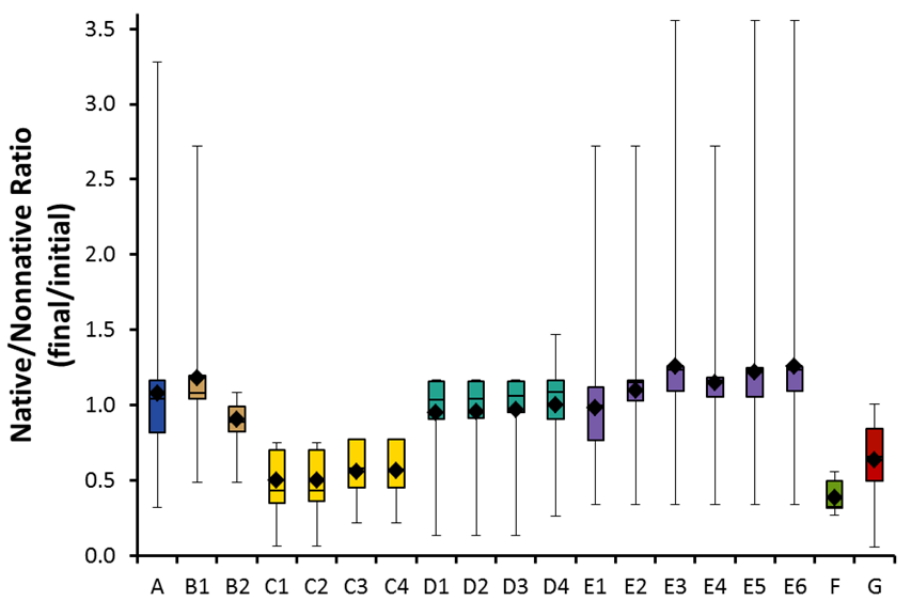

FIGURE G-6 Native/Nonnative Ratio Metric under Climate Change for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers) (Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum of the values for the 63 traces analyzed.)

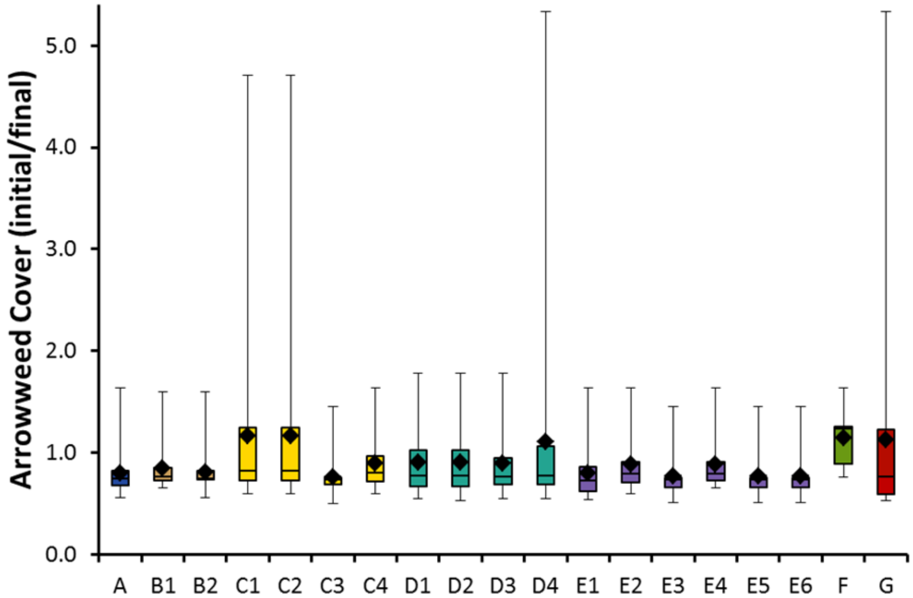

FIGURE G-7 Arrowweed Metric for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers) (Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum of the values for the 63 traces analyzed.)

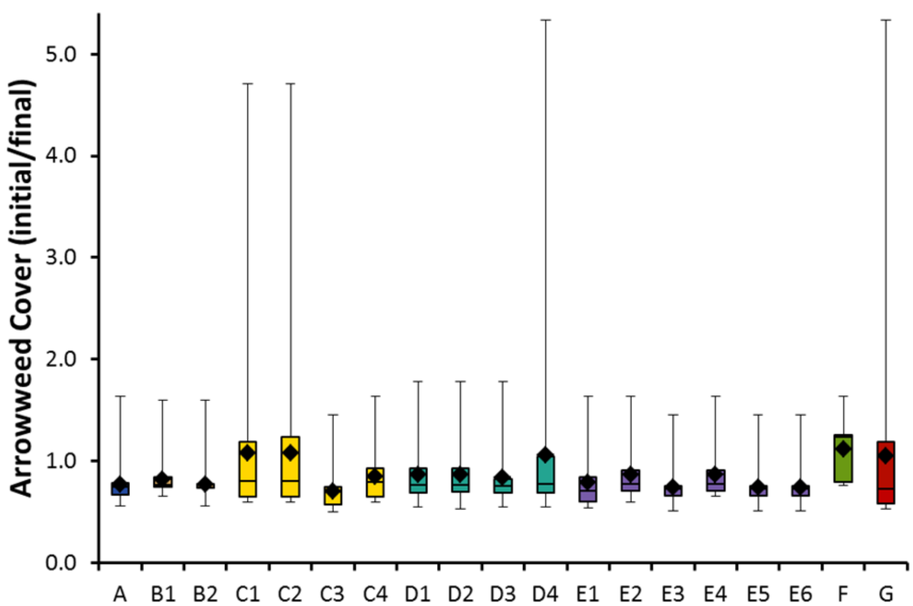

FIGURE G-8 Arrowweed Metric under Climate Change for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers) (Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum of the values for the 63 traces analyzed.)

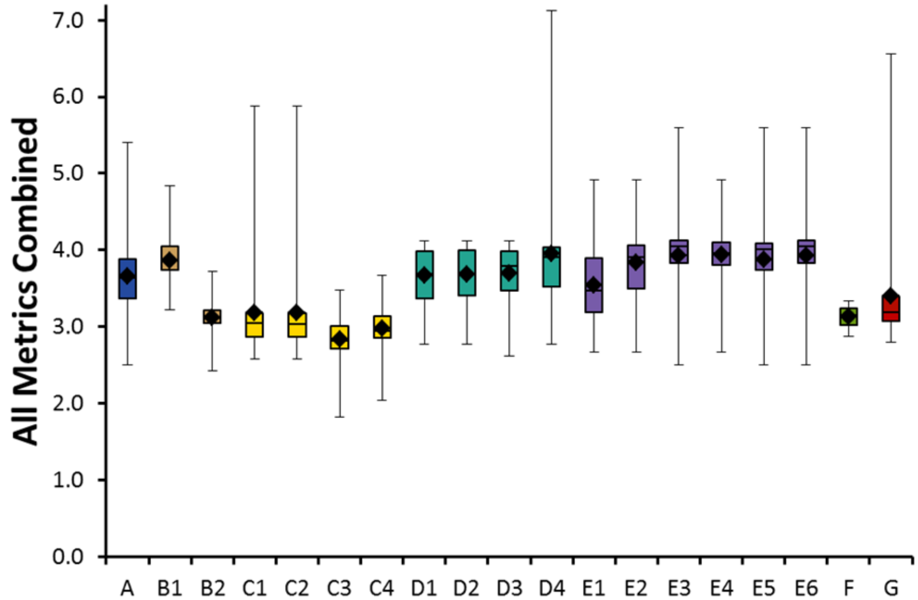

FIGURE G-9 Overall Combined Score for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers) (Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum of the values for the 63 traces analyzed.)

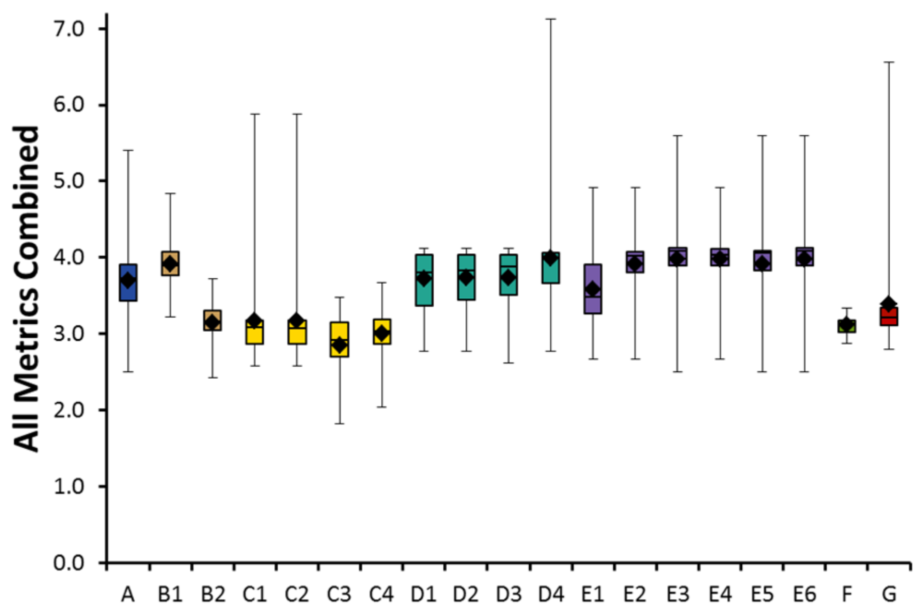

FIGURE G-10 Overall Combined Score under Climate Change for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers) (Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum of the values for the 63 traces analyzed.)

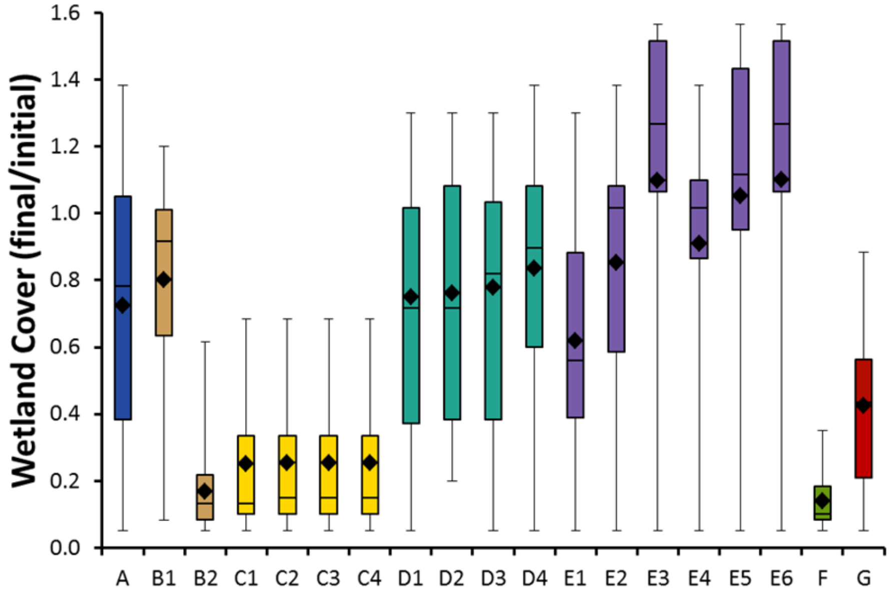

FIGURE G-11 Relative Change in Wetland Cover for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers) (Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum of the values for the 63 traces analyzed.)

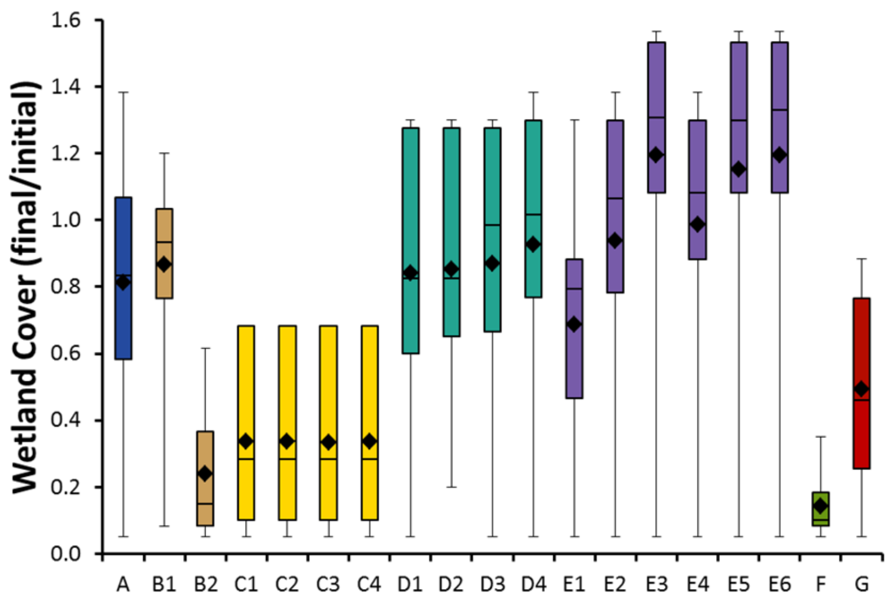

FIGURE G-12 Relative Change in Wetland Cover under Climate Change for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers) (Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum of the values for the 63 traces analyzed.)

APPENDIX H:

CULTURAL RESOURCES TECHNICAL INFORMATION AND ANALYSIS

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APPENDIX H:

CULTURAL RESOURCES TECHNICAL INFORMATION AND ANALYSIS

The assessment of potential impacts on cultural resources relied on three factors identified during the Long-Term Experimental and Management Plan (LTEMP) assessment process as the primary factors affecting the stability of historic resources in the canyons: (1) erosion (Thompson and Potochnik 2000; Damp et al. 2007; Spurr and Collette 2007), (2) inundation (Baker 2013), and (3) visitor effects (Bulletts et al. 2008, 2012; Jackson-Kelly et al. 2013). Metrics were formulated for these factors to quantitatively analyze the effects on cultural resources of the LTEMP alternatives based on modeling of discharge and sediment loads. The metrics are:

- Wind Transport of Sediment Index

- Flow Effects on Cultural Resources in Glen Canyon Index

- Time Off River Index

This appendix discusses the modeling of each metric and presents a detailed discussion of the modeling results. The metrics were developed through consultation with subject matter experts, findings in published papers and reports, and consideration of comments from cooperating agencies. See Section 3.8 for a more detailed description of Grand Canyon cultural resources and Chapter 2 for a detailed description of the LTEMP alternatives.

H.1 WIND TRANSPORT OF SEDIMENT

Prior to the construction of Glen Canyon Dam, periodic large-magnitude storm events would flood the Colorado River and deposit fluvial sediment onto high-elevation terraces. The deposited sediment buried and protected evidence of past human activity within the floodplain of the river. However, the dam's closure in 1964 trapped most of the sand that would have been transported into the Glen Canyon and Grand Canyon reaches of the Colorado River, and operations reduced the magnitudes of annual peak flows, which determine the elevation of the area scoured by high flows and at which new sand can be deposited. These changes decreased the renewal of sediment to high-elevation terraces downstream of the dam. With limited rejuvenation of sand, erosion can expose archaeological sites found along the riparian zone of the river.

In 2008, researchers found that, under the right conditions, sediment deposited along the riverbank above the elevation of normal operational flows can be transported by the wind and deposited on high-elevation terraces, many of which contain archaeological sites. This wind-blown sediment is thought to help stabilize archaeological sites on these high-elevation terraces. It was observed that this transfer of sediment occurred primarily in the spring months, when a reduced amount of rainfall and strong winds create optimal conditions for wind-blown sediment transport (Draut and Rubin 2008). A wind transport metric was developed based on principles identified by Draut and Rubin (2008). It is noted that the extent to which this process could stabilize cultural resources is unknown.

H.1.1 Wind Transport of Sediment—Methods

The Wind Transport of Sediment Index (WTSI) evaluates the availability of fine sediment for wind transport to cover cultural resources at higher elevations (i.e., those properties located at stages above 31,500 cfs). Optimal conditions for wind transport of sediment occur when (1) fine sediment is deposited by flows above the stage of normal operations and (2) low flows occur during the windy season, which exposes more sand for redistribution by the wind. These two conditions are accounted for by the Wind Transport of Sediment Index (WTSI) using the following equation (Eq. H1), where SLI is the Sand Load Index and FF is the Flow Factor*:*

$$WTSI = SLI \times Average(FF)_{2014-2033} \tag{H.1}$$

Both of the inputs for the metric (SLI and FF) are indices ranging from 0 to 1. The resulting Wind Transport of Sediment Index is a value from 0 to 1, where a value of 1 corresponds to the most potential movement of sediment by the wind, and therefore has the highest likelihood to contribute to the preservation of cultural resources. Both elements of the equation (SLI and FF) are limiting factors in the sense that the highest value between the two is the highest possible output. This mirrors the occurring environmental limitations—no more sediment can be transported than available, while, regardless of availability, wet sand is not likely to be easily transported by the wind.

The WTSI is calculated for a total of 63 scenarios representing different hydrologic (20 traces) and sediment conditions (3 traces), and weighted by the historical exceedance percentage of the sediment traces included in the scenario. Because of modeling limitations, environmental factors such as erosion of sandbars due to fluctuations in water level, rainstorm events which may further saturate soil, and vegetation barriers which could prevent sediment transport by the wind were not incorporated into the metric. Complex parameters like these would require more assumptions, which could result in less confidence in the model.

The SLI is an index of the potential sand deposited on sandbars along the river channel in Marble and Grand Canyons above normal stage elevations (31,500 cfs). The SLI is calculated as the ratio of the cumulative sand load at flows greater than 31,500 cfs relative to the total cumulative sand load at all flows. The sand load, or the mass of sand in transport by the river, is calculated at RM 30 and is computed by a version of the Sand Budget Model (Wright et al. 2010) for the 20-year LTEMP modeling period. A larger SLI (on a scale of 0 to 1) indicates a greater potential for sediment deposition. The SLI is described in more detail in Appendix E. The SLI was calculated using Equation H.2:

$$SLI = \frac{\sum_{2014-2033} Sand\ Load\ at\ dam\ discharges > 31{,}500\ cfs}{\sum_{2014-2033} Sand\ Load\ at\ all\ dam\ discharges} \tag{H.2}$$

The FF represents the relative exposure of dry, fluvial sand along the banks of the river available for wind transport. An increase or decrease in dam discharge will increase or decrease the downstream river elevation, respectively. Therefore, a lower discharge will expose a greater amount of sediment. For this metric, maximum daily flows above normal river stage (8,000 cfs) are considered increasing worse for sediment exposure. The maximum daily discharge (Q_{max}) modeled by GTMax-Lite represents the maximum discharge released from Glen Canyon Dam in cubic feet per second (cfs) and thus the extent of dry sand for each day. The yearly FF is the average of FF_{Daily} (Eq. H.3) for the spring months of March through June.

$$FF_{Daily} = \begin{Bmatrix} \text{if } \mathrm{Q}_{max} \le 8{,}000; & 1 \\ \text{if } 8{,}000 < \mathrm{Q}_{max} < 31{,}500; & 1.34 - 0.0000425 \times \mathrm{Q}_{max} \\ \text{if } \mathrm{Q}_{max} \ge 31{,}500; & 0 \end{Bmatrix} \qquad \text{(H.3)}$$

Note that although the FF only takes into account the months of March through June, the SLI incorporates the entire year. This is because the exposure of sand is most prominent during the windy season, but the sediment transported during those months is continuously built up throughout the year.

H.1.2 Wind Transport of Sediment—Results

WTSI values calculated for the LTEMP alternatives under historical flow and sediment inputs are shown in Figure H-1. The metric values represent the *potential* for sand to be transported to cultural sites rather than the actual transport that would occur or the level of protection that transport may provide to cultural sites. This results in some uncertainty with regard to actual differences in impact among the alternatives based on this metric. Our conclusions on relative impact are based on comparisons of the metric values calculated for Alternatives B, C, D, E, F, G and their long-term strategies, against Alternative A (the no-action alternative), which has the same basic operational discharge pattern as current operations under Modified Low Fluctuation Flows (MLFF). Although there is no published research for the direct impact of wind transport of sediment under MLFF on archaeological sites within the river corridor, recent research has shown that, under MLFF, approximately 1–3% of the gullies studied within reaches of the Colorado River between Glen Canyon Dam and the headwaters of Lake Mead showed obvious indication of filling by wind-blown sand (Sankey and Draut 2014).

Of the long-term strategies analyzed, one for each alternative was selected as most representative of the alternative as fully implemented. These representative long-term strategies were A, B1, C1, D4, E1, F, and G. All of the representative long-term strategies B1, C1, D4, E1, F, and G scored greater than Alternative A because they have more frequent high-flow experiments (HFEs). Long-term strategies B2, C3, E3, E5, and E6 rank below Alternative A. With the exception of B2, HFEs are not conducted for these strategies, and flows above 31,500 cfs would occur rarely, if at all. Recall that one of the primary assumptions for this metric is that flows above 31,500 cfs are the primary mechanism for sediment deposition at higher elevations. If there are no high flows to deposit sand at higher elevations along the banks of the river, there is no new sediment to be moved by the wind. Increased flow fluctuations in long-term strategy B2 cause it to rank below Alternative A.

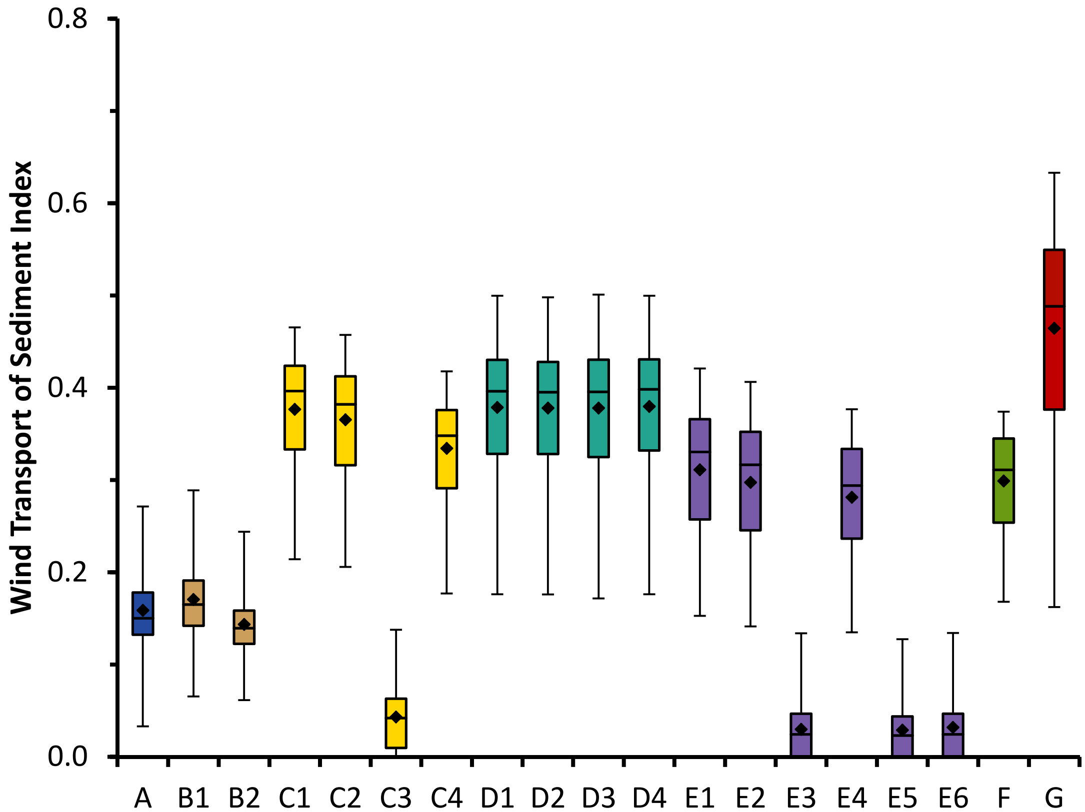


FIGURE H-1 Wind Transport of Sediment Index Values for the LTEMP Alternatives (letters) and Associated Long-Term Strategies (numbers) (Index values of 1 are considered optimal. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum.)

Alternative G scores the highest of all the alternatives, with an average WTSI nearly three times greater than Alternative A. With the highest number of HFEs and the lowest maximum daily flows during the windy months (Figure H-2), this alternative has parameters ideal for wind-transport of fluvial sediment to high-elevation terraces that contain cultural resources. The second highest scoring long-term strategy, D4, is not significantly different from D1, D2, D3, and C1 (statistical differences between means based on a three-factor analysis of variance (ANOVA) followed by Tukey's Studentized Range Test).

On the whole, the WTSI is highly correlated with the number of HFEs and the corresponding SLI. The relationship between SLI and HFEs is discussed in Appendix E. The similarity between WTSI and HFEs can be seen by comparing Figure H-1 with the average number of HFEs in Figure H-2. The WTSI is highly correlated with the SLI because the average maximum discharge between March and June for each of the alternatives is within 5,000 cfs (standard deviation of 0.05). With minimal difference in flow, the amount of sediment for distribution becomes the determining factor for the index. The exception to this is Alternative F. Figure H-3 shows a sample trace of the typical 8.23 million acre feet (maf) release year. In April,

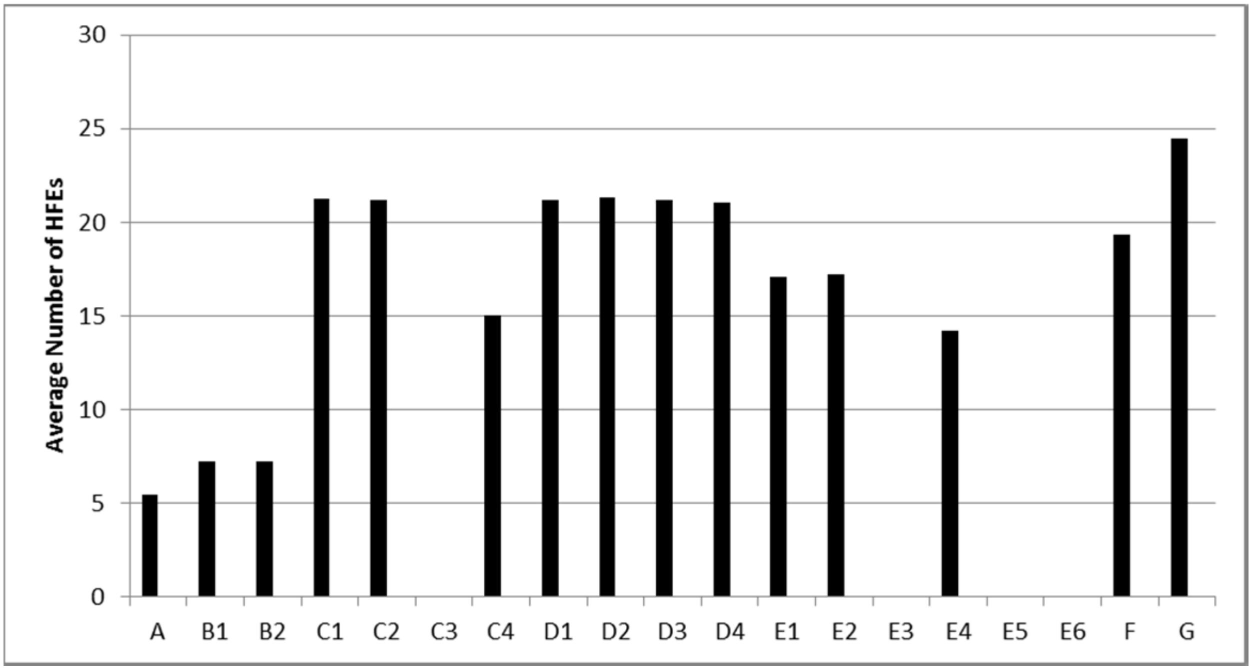


FIGURE H-2 Average Number of HFEs in the 20-Year LTEMP Period

May, and June, the discharge of Alternative F is higher than that of all other alternatives. Although Alternative F was determined to have the second highest potential sand deposition (highest SLI), it ultimately has an average WTSI value lower than Alternatives C, D, E, and G, as larger discharges of water create less ideal conditions for wind transport.

Long-term strategies C2 and E2 feature low summer flows and trout management flows (TMFs) when conditions trigger them. Reallocation of water volume from low summer flows can cause increased discharge in other portions of the water year. This reallocation combined with the high-flow portion of TMFs causes C2 and E2 to rank lower than their base alternatives. Similarly, the exclusion of spring HFEs in C4 and E4 decrease their WTSI in comparison to C1 and E1.

The WTSI is useful for understanding the interplay between the components of the alternatives. Alternatives that incorporate strategies for enhancing sediment retention (i.e., C, D, E, and G, which have reduced fluctuations or more even monthly volumes) have higher WTSI values. The metric also illustrates through Alternative F the effect that flow operations can have on wind transport. Index values are lower for Alternative F because the alternative features higher flows in the windier periods of the spring and summer, which negates some of the benefits of the higher sediment retention indicated in the SLI. Although the metric is beneficial for comparative and theoretical purposes, it reflects idealized conditions for wind transport of sediment that cannot be easily translated into actual site preservation. The extent to which wind transport of sediment can mitigate the erosion occurring to cultural sites on high elevation terraces remains unknown.

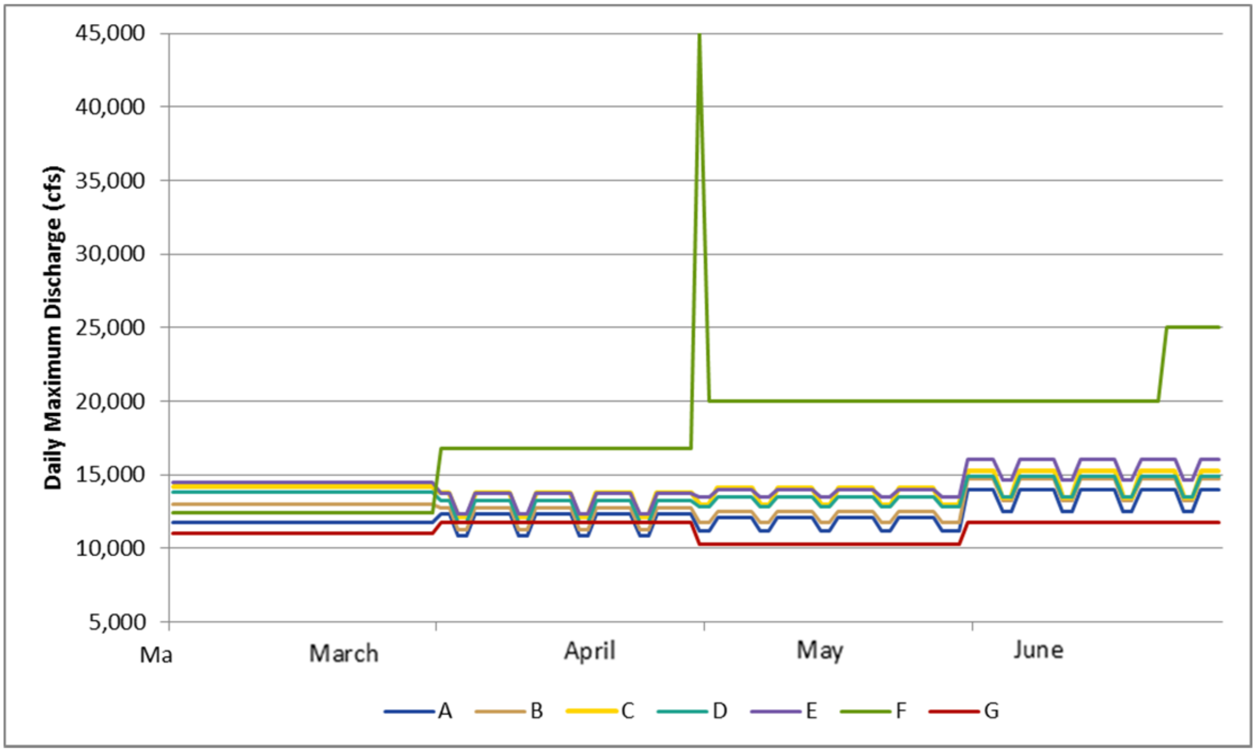


FIGURE H-3 Daily Maximum Discharge in a Typical 8.23-maf Water Volume Release Year from the Glen Canyon Dam during the Windy Season of March–June

H.2 FLOW EFFECTS ON CULTURAL RESOURCES IN GLEN CANYON

The construction of Glen Canyon Dam significantly scoured the immediate downstream Glen Canyon reach of the Colorado River and cut off nearly all of the sediment supply from upstream. Unlike further downstream sections of the river, a lack of significant tributaries in Glen Canyon results in very little sediment deposition on river banks of the canyon. In fact, high flows meant to distribute sediment have been shown to degrade terraces in the Glen Canyon reach (Grams et al. 2007). Archaeological sites located in Glen Canyon are also not associated with significant wind deposition of sediment (Anderson 2006). Without the rejuvenation of sediment, higher flows can increase erosion within the Glen Canyon, which is of concern for significant archeological sites.

Anderson (2006) identified 14 archaeological sites within Glen Canyon that were being affected by river-based arroyos or gullies. However, only one of these sites, commonly referred to as Ninemile Terrace, was determined to have erosional features that are unequivocally related to direct impacts of river operations. Bank stability at Ninemile Terrace, and other terraces having the potential to contain cultural resources, is partially dependent on the accumulation of material at the base of the slope. Removal of this protective material through erosion leaves the lower-bank material prone to a continuing cycle of undercutting, collapse, and removal. This, in turn, contributes to slumping of the upper-bank material, whether dry or saturated. The flow at which the base of the slope begins to erode serves as the “flow elevation threshold.” Flows at or above this threshold have the potential to adversely affect cultural resources through bank erosion and destabilization (Baker 2013). Time-lapse photography from the November 2012 HFE shows that the inundation of the existing base of the slope at Ninemile Terrace occurs at a flow of 23,200 cfs.

Ninemile Terrace reflects many characteristics of other sites in Glen Canyon and was considered representative of other Glen Canyon terrace sites for determining the effects of water flow on high-elevation terraces. In the absence of direct field measurements to further clarify a flow elevation threshold, the flow rate of 23,200 cfs was selected by Grand Canyon Monitoring and Research Center (GCMRC) staff as an approximate measure to represent the flow elevation above which erosional processes could contribute to impacts that have the potential to adversely affect cultural resources.

H.2.1 Flow Effects on Cultural Resources in Glen Canyon—Methods

Impacts on cultural resources in the Glen Canyon reach were determined by calculating the number of days per year that the maximum daily flow would be >23,200 cfs. Therefore, a higher number represents the increased potential of erosion of terraces that contain cultural resources. The maximum daily flow is used to capture all instances where flow is high enough to contribute to erosional processes. As with the WTSI, a total of 63 scenarios of different hydrologic and sediment conditions were analyzed.

This metric determines the relative difference among alternatives for the potential impacts of flow on cultural resources. Research would be needed to determine the number of days of high flow that would produce noticeable or extensive impacts on cultural sites.

H.2.2 Flow Effects on Cultural Resources in Glen Canyon—Results

The number of days per year flows would be >23,200 cfs under each alternative are shown in Figure H-4. The average number of days flows would be >23,200 cfs ranges from 18 to 36 days among the alternatives. High maximum values of 50–77 days would occur under all alternatives (as noted by the upper whisker) and would occur in years with abnormally high water volumes released from Glen Canyon Dam.

Alternative A has the highest number of days per year flows would be >23,200 cfs. Alternative A most closely represents the current conditions of MLFF. Long-term strategies C3, E3, E5, and E6 (long-term strategies with no HFEs) have average values that are lower than under Alternative A, but by no more than 3 days. Alternative F would have the highest number of days per year flows would be >23,200 cfs with an average of 14 days per year more than under Alternative A. Alternative F, therefore, has the highest potential for impacts on terraces that contain cultural resources in Glen Canyon. The higher number of days under Alternative F results from the relatively high spring flows between May and June (Section 2.2.6). The remaining alternatives have an average number of days per year flows would be >23,200 cfs within 4 days of those under Alternative A.

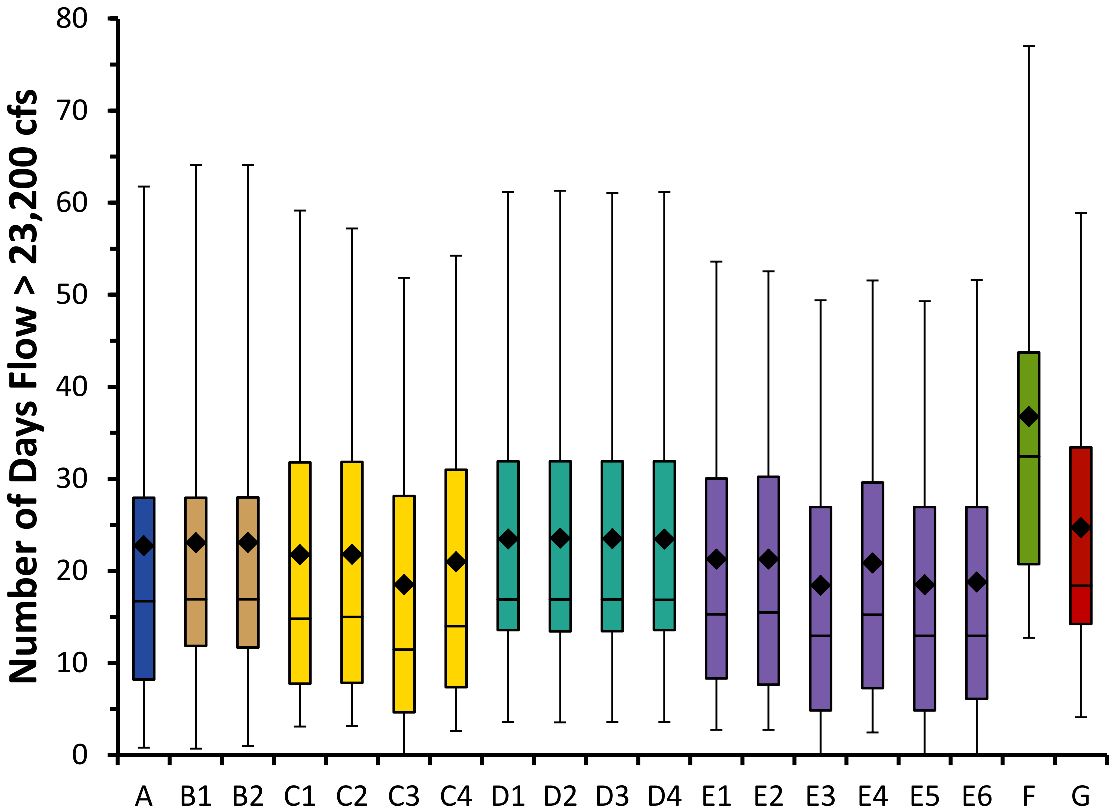


FIGURE H-4 Number of Days per Year Flows Would Be >23,200 cfs under LTEMP Alternatives (Letters) and Long-Term Strategies (Numbers) (Flows of this magnitude have the potential to affect cultural resources in Glen Canyon. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum.)

Besides the high spring flows of Alternative F and HFEs under all alternatives, operational changes within long-term strategies seem to have minimal effect on the number of days per year flows would be >23,200 cfs. Long-term strategy B2 includes tests of hydropower improvement flows (i.e., operations with wider water release fluctuations in high electrical demand months than the base operations of B1). Although hydropower improvement flows increase within-day flow fluctuations, in most cases, the altered maximum flow does not exceed 22,000 cfs. Therefore, long-term strategies B1 and B2 have nearly identical values and are not significantly different. Long-term strategies C2, D3, E2, and E5 all have low summer flows. Low summer flows result in higher flows at other times of year, but do not affect the number of days per year flows would be >23,200 cfs, and these long-term strategies will not have any effect on this metric. TMFs would also have minimal effect on this metric.

Although there are differences among alternatives in the number of HFEs (Figure H-2), these differences have little effect on the number of days per year flows would be >23,200 cfs. This occurs because HFEs are relatively short (Figure H-5), and the large volume released under the HFE must be compensated by releasing less water at other times of the year (Figure H-6).

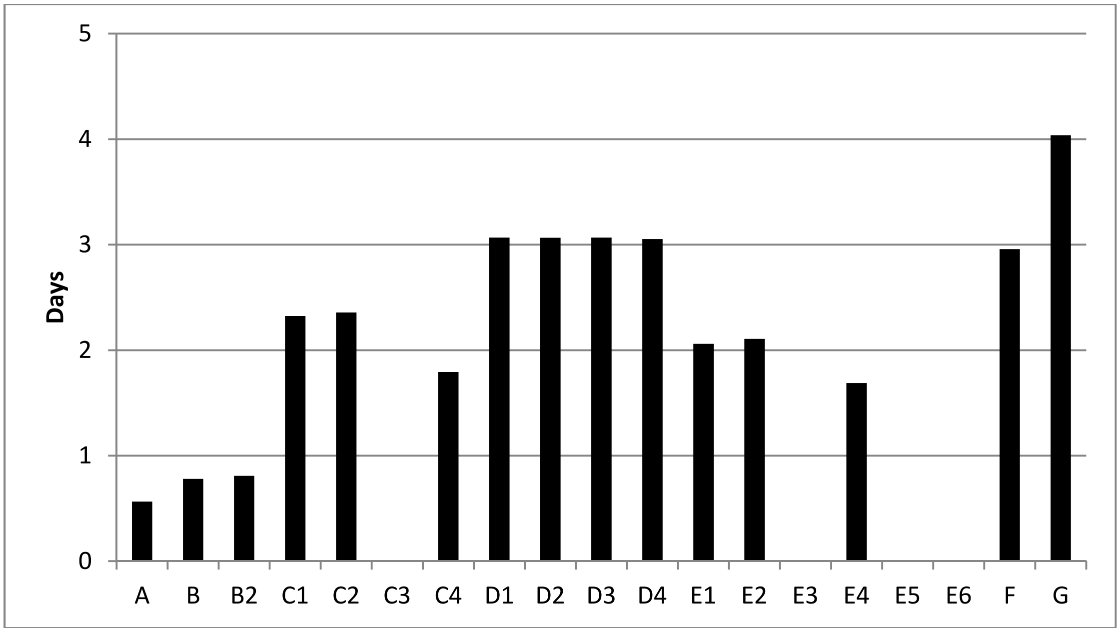


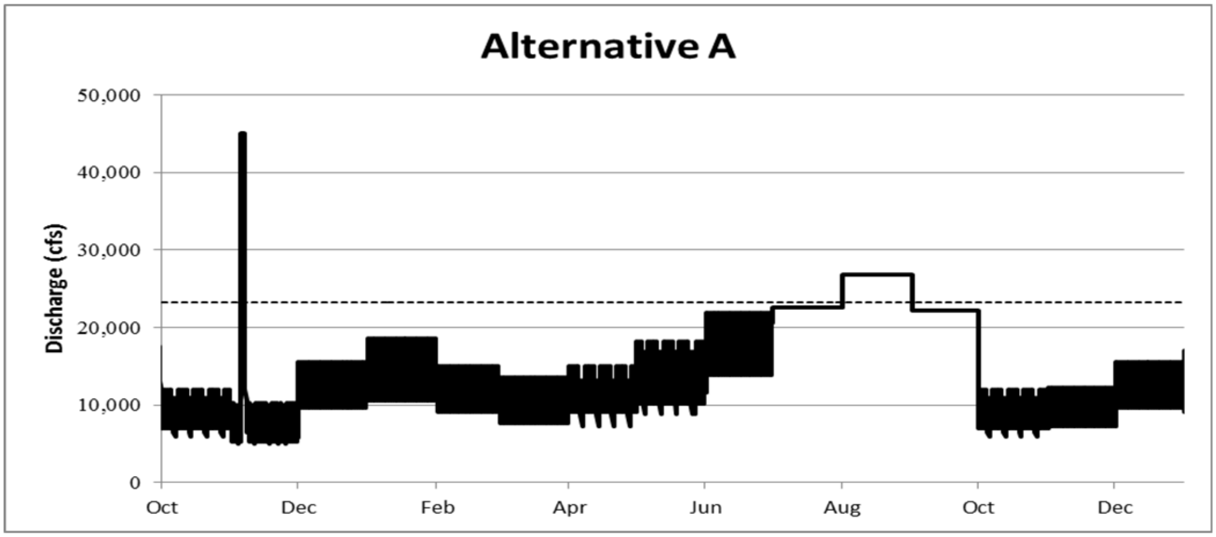
FIGURE H-5 Average Number of Days of an HFE Event per Year

Since all alternatives must release the same annual volume of water, alternatives with HFEs may have lower releases at other times of years than those without. The effect on the metric would be greater in years of high volume ($\geq$10 maf) when equalization flows would be implemented according to the Interim Guidelines (Reclamation 2007).

This explains why Alternative A and B, with minimal HFE events, have nearly the same metric value as alternatives like Alternative C with more than four times the number of HFEs (Figure H-2). Although Alternative C has two HFEs in Figure H-6 and Alternative A has only one, Alternative A must release more water in August to compensate. Historically, precipitation was higher than conditions in recent years; therefore, equalization flows may be triggered less frequently and days above 23,200 cfs might be less than those based on historical flows. The 50th and 25th percentile values are more applicable to recent climate conditions seen in the Glen Canyon region. It is also noted that the variability (noted by the length of box) in the value is a result of the variability in the release volume between water years, HFEs, and the interaction between the two for a particular alternative.

H.3 TIME OFF RIVER

Greater discretionary time for whitewater rafters to explore the canyons downstream of Glen Canyon Dam increases the likelihood that they could have an impact on archaeological sites by creating trails to sites or looting or vandalizing sites. When the river is moving at a faster pace and boat travelers arrive at their destination earlier, their discretionary time off river increases. It is therefore hypothesized that higher flows may increase the potential for adverse human contact with archeological sites.



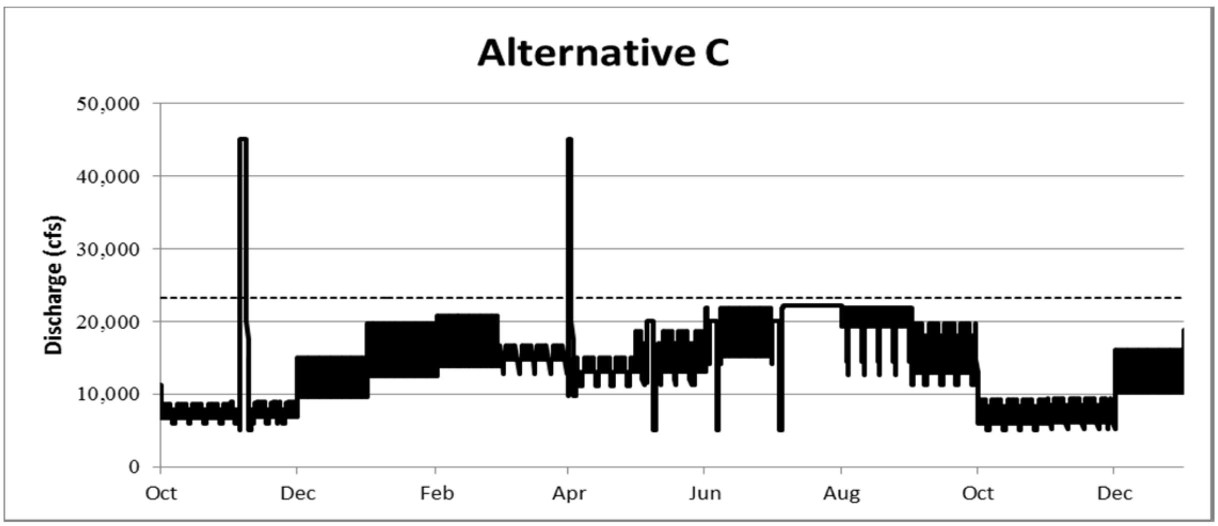


FIGURE H-6 Modeled Glen Canyon Dam Discharge for the Same Year (the line represents 23,200 cfs)

H.3.1 Time Off River—Methods

The Time Off River Index (TORI) represents the degree to which flows could affect visitor potential to interact and disturb cultural sites. Grand Canyon visitor numbers vary depending on the time of the year. Recreational activity is more common in the warmer summer months, less so in the spring and fall months, and even less in the colder winter months. The yearly TORI (Eq. H.4) is the ratio of the sum of seasonal ratios which designate flows ideal for minimal visitor-site interaction. Summer has the highest weight (0.54) while winter has the lowest (0.15) and spring and fall are in between (0.31). The TORI is a 0–1 value, where 1 equals the least discretionary time for visitors to access archaeological sites, and, therefore, the lowest potential for impacts on cultural sites.

$$TORI = \{0.15\left(\frac{\sum_{winter} ORFF}{\sum Days_{winter}}\right) + 0.31\left(\frac{\sum_{\frac{spring}{fall}} ORFF}{\sum Days_{\frac{spring}{fall}}}\right) + 0.54\left(\frac{\sum_{summer} ORFF}{\sum Days_{summer}}\right)\} \quad (H.4)$$

An overall annual mean TORI value for the 20-year modeling period was developed for each alternative and used as the performance metric (Eq. H.5).

$$TORI = Average\ (TOR_{annual})_{2014-2033} \quad (H.5)$$

The Off River Flow Factor (ORFF) represents the potential for discretionary time off river. The discharge level at which boats begin to exceed typical river travel times is 10,000 cfs. However, once flows reach above 31,500 cfs, visitors are more likely to stay at campsite areas rather than travel in a turbulent river. Daily average flows (Q_{avg}) represent the average release from Glen Canyon dam in cfs. Average daily discharge from the dam was modeled in GTMax-Lite. The ORFF is a 0–1 value, where 1 indicates the lowest potential for discretionary time off river and therefore the lowest potential for increased visitation of archaeological sites. Specifically, the average daily ORFF is assigned as follows (Eq. H.6), where the value within the brackets in the right column is assigned to $ORFF_{Daily}$ if the equation in the left column is satisfied:

$$ORFF_{Daily} = \begin{Bmatrix} \text{if } Q_{avg} \leq 10{,}000; & 1 \\ \text{if } 10{,}000 < Q_{avg} < 31{,}500; & 1.465 - 0.0000465 \times Q_{avg} \\ \text{if } Q_{avg} \geq 31{,}500; & 0 \end{Bmatrix} \quad (H.6)$$

As with the WTSI, a total of 63 scenarios of different hydrologic and sediment conditions were analyzed.

H.3.2 Time Off River—Results

TORI does not specify how much additional discretionary time off river a visitor may experience. Instead, TORI is intended to determine the potential for visitors to spend more time off of the river exploring, which could result in more cultural resources being visited and possibly affected, by examining the flows under the various alternatives as compared to Alternative A.

A summary of TORI results is provided in Figure H-7. All of the alternatives and their long-term strategies performed similarly within this metric. Values of TORI under long-term strategies B1, B2, C2, and C4 were not significantly different than those under Alternative A. Although Alternatives D, E, and G rank the highest with regard to this value (and thus would be expected to have the lowest impact), the minimal differences in the metric values from Alternative A would likely indicate that they would not have noticeable impacts on visitor-site interactions.

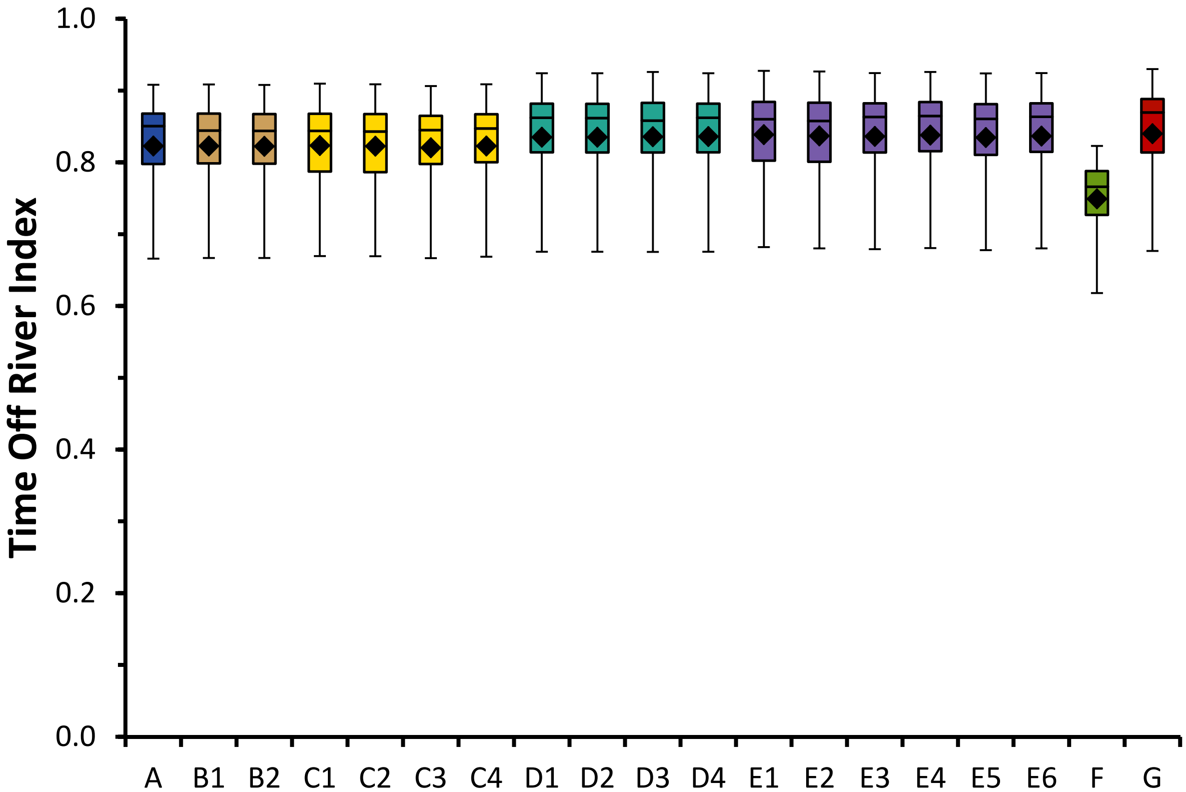


FIGURE H-7 Time Off River Index Values for All LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers) (Index values of 1 are considered optimal. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum.)

The difference between the TORI for Alternative F and the other alternatives is largely due to flows during the spring and early summer that are generally at or above 20,000 cfs, while all other alternatives have daily flows that average between 8,000 and 12,000 cfs. Figure H-8 shows the difference in average discharge between Alternative F and the other alternatives. Although Alternative F has very low flows in December and January, the alternative has flows that are more than 7,000 cfs higher than other those under other alternatives in spring and early summer months.

TORI values would be higher in years of high volume (>10 maf) when relatively high equalization flows would be implemented according to the Interim Guidelines (Reclamation 2007). However, these relatively high releases result from high inflow volumes in wet years, are unavoidable, and differ little among alternatives.

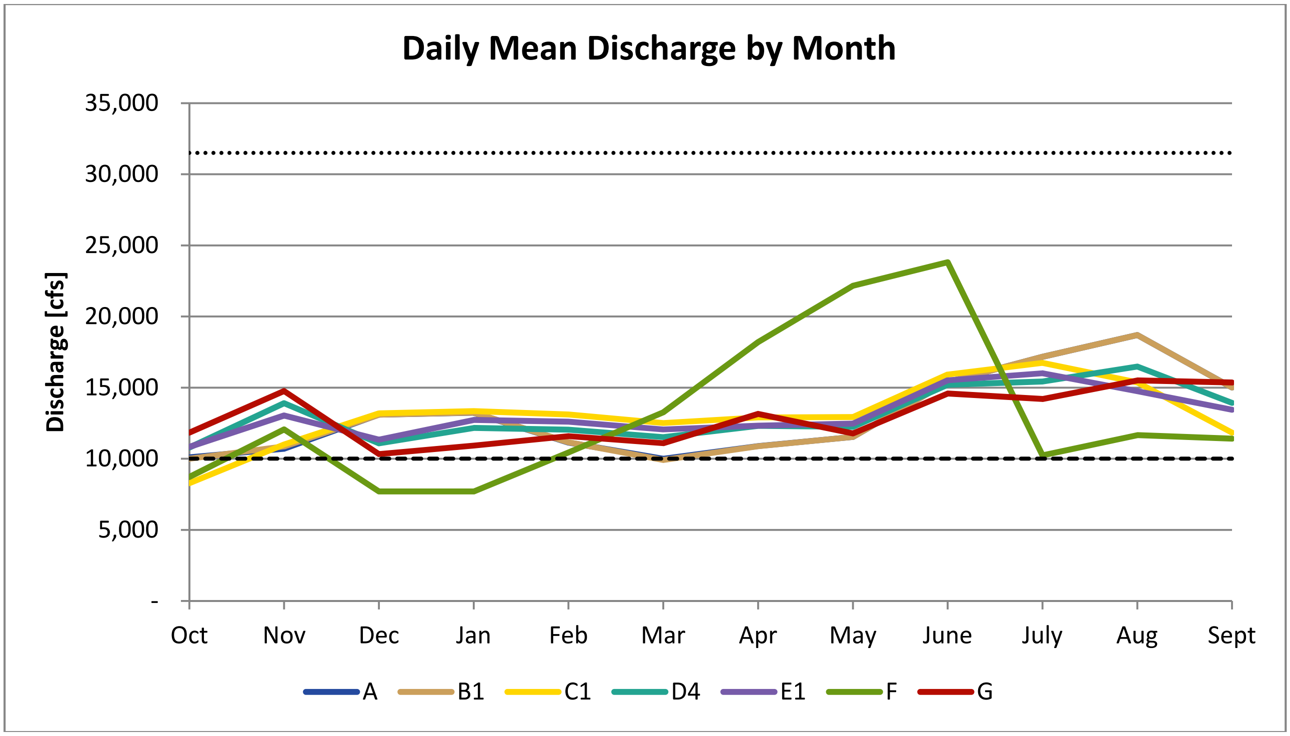


FIGURE H-8 Daily Average Discharge for Representative Long-Term LTEMP Strategies

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APPENDIX I:

TRIBAL RESOURCES TECHNICAL INFORMATION AND ANALYSIS

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APPENDIX I:

TRIBAL RESOURCES TECHNICAL INFORMATION AND ANALYSIS

Section 4.9 of the Draft Environmental Impact Statement (DEIS) assesses and compares the potential impacts Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) alternatives could have on resources important to federally recognized Tribes. Indian Tribes have been recognized by the courts as “domestic dependent nations.” They were sovereign entities before the arrival of Euro-American colonizers and continue to exercise that sovereignty within their reserved lands. Consultation between Tribes and the federal government is consultation between sovereign entities. Even when they have been removed from their ancestral lands, Tribes often retain strong ties to culturally important resources in their traditional homelands. When those resources are located on federal lands or could be affected by federal or federally licensed undertakings, federal agencies are required to take into account those potential impacts in their decision-making (see Table I-1).

The nature and degree of impacts that an undertaking could have on resources important to Tribes is best evaluated with significant input from the Tribes themselves. To this end, the Bureau of Reclamation (Reclamation) and National Park Service (NPS) have sought to include input from all federally recognized Tribes that have traditional, historical, cultural, or religious ties to the canyons. Forty-three Tribes with potential ties to the canyons were notified of the LTEMP EIS project by mail with telephone follow-up and invited to participate. Of these, six chose to become cooperating agencies; two Tribes chose to consult, but not as cooperating agencies; and nine chose not to actively consult, but to be kept informed of project developments. Thirteen Tribes chose not to participate. There was no response from the remaining twelve Tribes (see Appendix N).

Assessing the comparative impacts of the LTEMP alternatives on Tribal resources presents a challenge both (1) because of the holistic view of the canyons that Tribal members tend to take, in which all elements of the environment are interconnected, so that effects on one part of the environment affects the whole, because there is no single “Tribal view” held by all members of all Tribes, and (2) because knowledge of the location of some of the most sacred places is not shared with outsiders. Not all Tribes agree with each other on all issues, but some common themes and issues did emerge from discussions with Tribal representatives, review of canyon monitoring reports produced by the Tribes, and ethnographic sources produced by or for

TABLE I-1 Federal Regulations and Executive Orders Pertaining to Consultation with Tribes

40 CFR 1506.6 *Cooperating Agencies*
43 CFR 46.225 *How to Select Cooperating Agencies*
E.O. 13175 *Consultation and Coordination with Indian Tribal Governments*
Section 106 of the *National Historic Preservation Act (1966 as amended)*
36 CFR 800.2 (c) (2) *Participants in the Section 106 Process*

the Tribes. For many Tribes, environmental features considered inanimate in Western cultures are seen as imbued with life; in some cases, such as with the Colorado River and the Little Colorado River, they are considered deities. Various Tribes regard the canyons as sacred space, the place where their people emerged into this world, the home of their ancestors, the residence of the spirits of their dead, and the source of many culturally important plant, animal, and mineral resources. Many Tribes view themselves as connected to the Colorado River and its canyons and as stewards over the living world around them including water, earth, plant life, and animal life. This holistic view encompasses subject areas considered in this DEIS, and Tribal perspectives on these resources are found throughout the document. The values the Tribes place on the river and its canyons are significant and real, but often intangible; therefore, they are not easily or are only partially quantifiable. In addition, many of the values and resources that are most important to the Tribes are not directly affected by differences in the patterns of release of water from the Glen Canyon Dam.

Knowledge of some of the most sacred and sensitive places and resources in the canyons is esoteric, known chiefly by elders and initiated religious practitioners. Only they can provide information on what is most sacred and what can be revealed in a public format such as an EIS. Funding was provided to support Tribes in obtaining and providing these important perspectives on the river and the canyons. Appendix N details the efforts undertaken to obtain Tribal input regarding resources important to Tribes that could be affected by the operation of Glen Canyon Dam and proposed associated actions. These efforts included face-to-face meetings, webinars, and conference calls. The Tribes that chose to act as cooperating agencies also were afforded the opportunity to provide text for the DEIS, and to review and comment on the draft document before it was released to the public.

Although many aspects of the effects on Tribal resources are not quantifiable, quantifiable measures of effects on the canyon environment were found that reflect important Tribal values and could stand as proxies for those values. These include effects on the diversity of riparian vegetation, effects on marshes and other wetlands, effects of large-scale taking of nonnative fish for fish management purposes, effects on Tribal water rights, and factors that could affect Tribal economics. Tribes are concerned with natural resources beyond plant and aquatic life in the canyons. Bighorn sheep, songbirds, and butterflies are among the indicators of canyon health mentioned by Tribal members. Many of these resources are considered qualitatively in the wildlife section of the DEIS (Sections 3.7 and 4.7) and can be reviewed and considered by Tribal specialists and representatives.

I.1 QUANTIFIABLE MEASURES USED TO ASSESS IMPACTS ON TRIBAL RESOURCES

I.1.1 Riparian Diversity

Among the quantifiable projected impacts are those on riparian vegetation, the plant life likely to be most directly affected by flow management at the Glen Canyon Dam. The Western concept of "ecosystem" comes close to Tribal views of interconnectedness. Plant life is a fundamental part of most ecosystems. The state of riparian vegetation is a good indicator of the state of the canyon ecosystem as a whole. Thriving, diverse vegetation communities indicate a healthy ecosystem. Models of future plant diversity along the river provide a quantitative indicator of ecosystem health. Many Tribes give native species and nonnative plant species equal value as forms of life to be respected. Therefore the measure presented here includes plant communities dominated by both native and nonnative plants. For a discussion of diversity in native plant communities, see the Native Diversity Index in Appendix G.

A metric for vegetation community diversity in the riparian zone has been developed based on the results of a state and transition model for Colorado River riparian vegetation downstream of Glen Canyon Dam. This model has been developed to compare the effects of alternative flow regimes on Colorado River riparian vegetation. The model is discussed in Section 4.6.1. For a more detailed discussion of the model, see Ralston et al. (2014) and Appendix G. The model uses characteristics of annual dam operations to predict transitions from one plant community type to another on sandbars and channel margins in the riparian zone. The model projects transitions over a 20-year period for each alternative and long-term strategy analyzed. Relative change in the diversity of vegetation community types on sandbars and in channel margins is projected using the Shannon-Weiner Index for richness/evenness[1] and a diversity score calculated by comparing the final (modeled) diversity to the initial diversity (change in diversity = $\text{diversity}_{final}/\text{diversity}_{initial}$). A healthy ecosystem is characterized by a high degree of species diversity, represented here by diversity in vegetation community types. A total diversity score was calculated that included nonnative (primarily tamarisk) as well as native communities including the invasive arrowweed. Table I-2 shows the seven vegetation states, or plant community types, that were considered. The species associated with a state all respond similarly to Colorado River hydrologic factors such as depth, timing, and duration of inundation.

The model consists of six submodels based on the following landforms: lower separation bars, upper separation bars, lower reattachment bars, upper reattachment bars, lower channel margins, and upper channel margins. Upper and lower landforms are divided at the 25,000 cfs

TABLE I-2 Vegetation States

Vegetation States
Bare Sand
Marsh (Common Reed Temperate Herbaceous Vegetation)
Shrub Wetland (Coyote Willow-Emory Seep Willow Shrubland/Horsetail Herbaceous Vegetation)
Tamarisk (Tamarisk Temporarily Flooded Shrubland)
Cottonwood-Willow (Fremont Cottonwood/Coyote Willow Forest)
Arrowweed (Arrowweed Seasonally Flooded Shrubland)
Mesquite (Mesquite Shrubland)

1 For a discussion of the Shannon-Weiner Index, see Appendix G.

flow stage (see Section 3.3.1.1 for a description of these landforms). The model projects transitions between vegetation states, based on a set of rules developed for each submodel, driven by hydrologic events. The model includes a subset of states and transition rules for each submodel. The states and transition rules for the upper portions of the bars and channel margin are the same because of the similarity of plant community types and responses to flow characteristics. The transition rules are based on the effects of scouring, drowning, desiccation, and sediment deposition on riparian plant species. Transition rules are presented in Table G-3 in Appendix G.

Figure I-1 shows the weighted diversity scores for the seven LTEMP alternatives and their associated long-term strategies (described in Appendix C). The higher the score, the greater the diversity of plant community types. A score of 1.0 indicates that the current degree of plant community diversity is projected to be maintained. A score greater than 1.0 indicates increased diversity, less than 1.0 a loss of diversity. The mean scores for each alternative fall into a somewhat wider range than the Native Diversity scores presented in Appendix G. They range from 0.70 under Alternative F to 0.97 under long-term strategy B1. Alternative A (no action alternative) scored 0.95. Alternatives D and E scored above 0.90 under all of their associated long-term strategies.

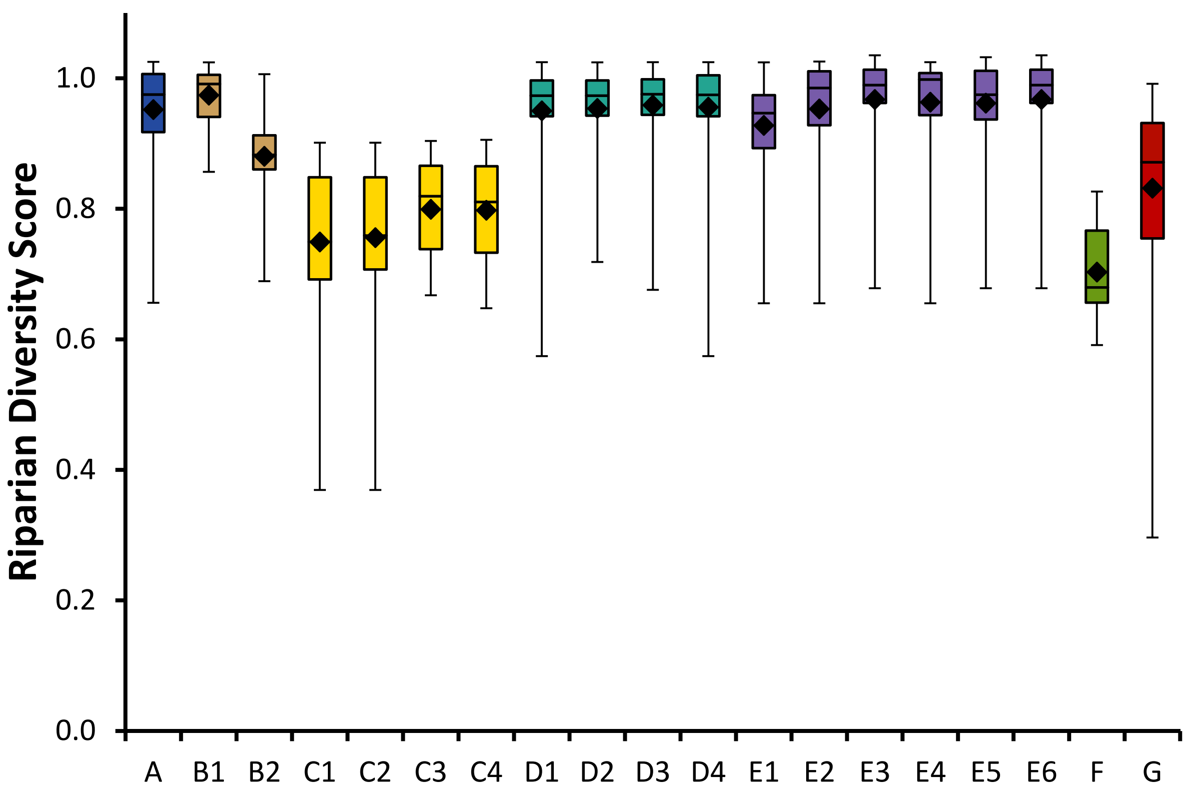

FIGURE I-1 Riparian Diversity for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers)

The results indicate that on average all alternatives would result in a small decrease in total vegetation state diversity over the 20-year LTEMP modeling period. The loss in diversity would be greatest under those long-term strategies where there is an increase in the area covered by the tamarisk community type (see Table 4.8-3). Alternatives where tamarisk[2] would increase are characterized by high flows (high-flow experiments [HFEs] or ≥30 days with flows >20,000 cfs), which serve to distribute seed, and/or low flows in the growing season (May–September) that allow seedlings to establish themselves. Once established, tamarisk is tenacious. When it does transition, it is most often to bare sand.

Under climate change assumptions, the modeled pattern shows very little difference from the historical-based assumptions (Figure I-2). There is a minimal overall increase in mean diversity scores, suggesting that the difference would be barely perceptible on the ground.

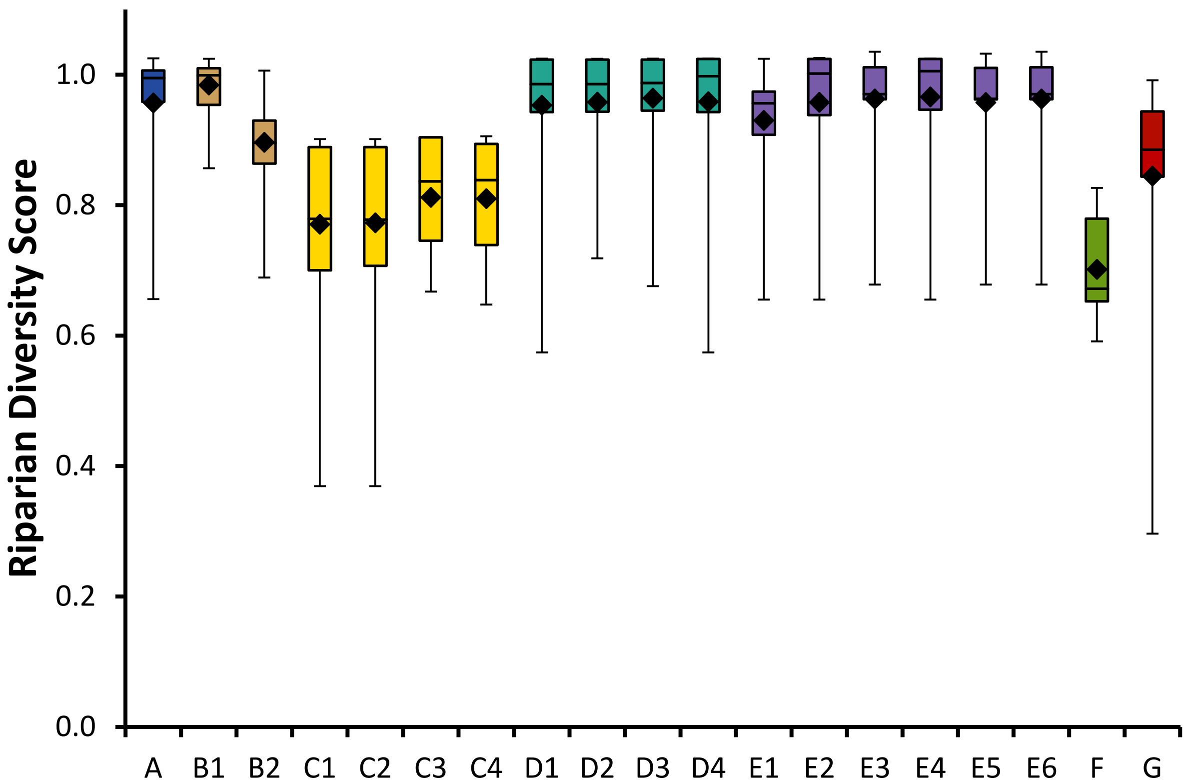

FIGURE I-2 Riparian Diversity under Climate Change Assumptions for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers)

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[2] The model takes into account the effects of scouring, drowning, desiccation, and sediment deposition, but does not account for the effects of the tamarisk leaf beetle or tamarisk weevil. These two insect species may result in a reduction in the amount of live tamarisk in the river corridor.

I.1.2 Wetland Abundance

Some Tribes (e.g., the Hopi) see the health of canyon wetlands as an indicator of canyon health (Yeatts and Huisinga 2013). Assessments of the projected state of wetland cover over the next 20 years can be derived from the state and transition model discussed above. Two of the model states listed in Table I-2 are wetland community types: Common Reed Temperate Herbaceous Vegetation, a marsh community; and Coyote Willow-Emory Seep Willow/Horsetail Herbaceous Vegetation, a shrub wetland community.

Wet marsh communities of flood-tolerant herbaceous species that occur on low-elevation areas of reattachment bars have developed in response to frequent inundation. Wet marsh communities (with common reed and cattail the dominant species) occur on fine-grained silty loam soils in low-velocity environments on lower areas of eddy complex sandbars; although they are easily scoured by high flows, they can redevelop quickly. Shrub wetland communities (with coyote willow, Emory seep willow, and horsetail the dominant species) occur on sandy soils of reattachment bars and channel margins, below the 25,000 cfs stage, that are less frequently inundated.

Wetland communities generally transition only from bare sand or other wetlands; they can transition back to bare sand or to arrowweed, tamarisk, or cottonwood-willow communities. An increased occurrence of transitions from bare sand to wetlands and/or maintenance of wetlands (lack of transitions to other community types) would result in greater wetland cover. Large daily fluctuations increase the area of saturated soil and thus the sandbar area available for wetland species establishment. The reduction of daily fluctuations may increase the establishment of wet marsh species at lower elevations and promote the transition of higher elevation marshes to woody species such as tamarisk or arrowweed. Periodic flooding and drying tends to increase diversity and productivity in wetland communities. Although low-elevation plants in marshes in Marble Canyon and Grand Canyon, such as cattail, common reed, and willow, may become buried with coarse sediment, recovery generally occurs within 6 to 8 months. Low steady flows can cause some wetland patches to dry out, resulting in considerable plant loss. Sustained high releases reduce wetland vegetation cover to less than 20% on lower reattachment bars. Extended high flows typically scour herbaceous vegetation; however, most woody plants often remain. Thus, extended high flows followed by extended low flows in the following growing season result in a transition from shrub wetland to a cottonwood-willow community on channel margins. A transition from marsh to shrub wetland occurs on lower reattachment bars with 4 years of consecutive seasons of low fluctuating flows or non-growing season sustained low flows (Ralston et al. 2014).

The relative change in cover of these wetland community types was calculated from the state and transition model results. The number of years each of the wetland states occur in each submodel is projected for the 20-year LTEMP modeling period. The results for the seven alternatives and their long-term strategies are presented in Figure I-3. A mean score of 1.0 indicates no change from initial conditions is expected. A score greater than 1.0 indicates an increase in wetland cover; a score of less than 1.0 indicates a loss in wetlands. Alternative F scored the lowest (0.14), and long-term strategy E6 scored the highest (1.10). Alternative A scored 0.72.

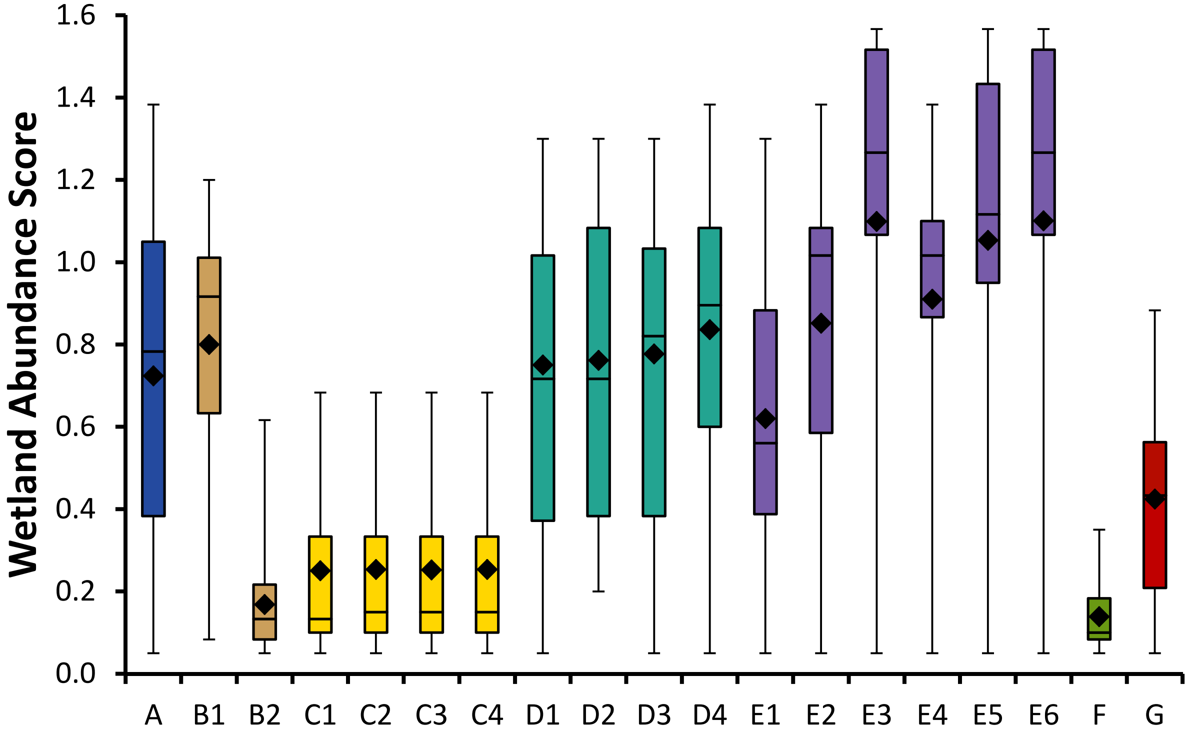

FIGURE I-3 Wetland Abundance for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers)

Only Alternative E, long-term strategies E3, E5, and E6—none of which have HFEs—show an increase in wetland cover (based on mean scores); all others show a decrease. However, long-term strategies B1, D1, D2, D3, D4, E2, E3, E4, E5, and E6 all scored higher than Alternative A. The alternatives with high scores are characterized by fewer extended high flows (greater than 20,000 cfs) and fewer extended low flows (less than 10,000 cfs) than Alternative A. There is enough water to sustain wetlands, but not too much inundation to support them over time. A large decrease in wetland community cover occurs under B2, all Alternative C long-term strategies, Alternative F, and to a lesser extent Alternative G. Frequent extended low flows or extended high flows followed by extended low flows tend to result in the transition of wetlands to other plant community types. Repeated seasons of extended high flows, or sufficiently high flows during one season, can remove wetlands, resulting in bare sand landforms.

Under climate change assumptions, the overall pattern remains the same for all alternatives, except that the Alternative F score increases slightly, as seen in Figure I-4. On average, scores increased by 0.08, with Alternative F showing only a negligible increase in the mean score (0.0017).

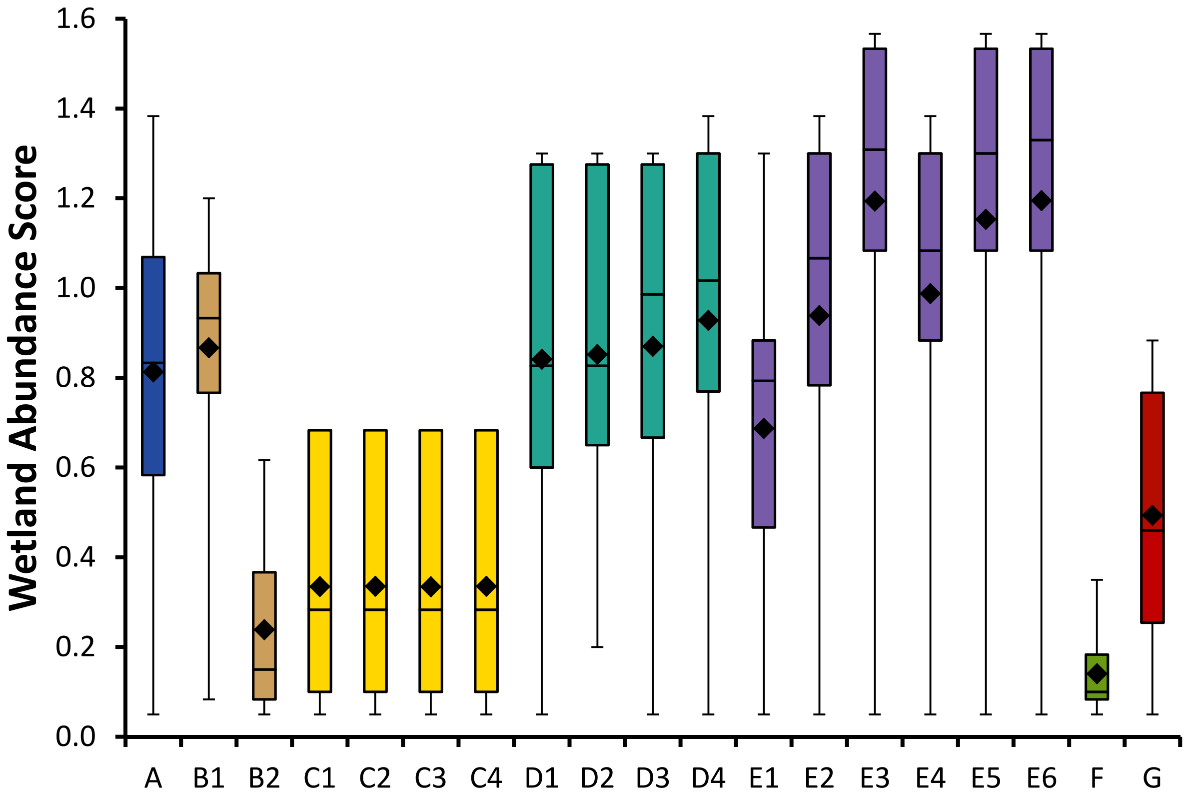

FIGURE I-4 Wetland Abundance under Climate Change Assumptions for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers)

I.1.3 Trout Management Flows

Reclamation and NPS are required under the U.S. Fish and Wildlife Service (FWS) biological opinion related to the *Non-native Fish Control Downstream from Glen Canyon Dam Environmental Assessment* (Reclamation 2011) to take steps to protect and encourage the recovery of endangered humpback chub (*Gila cypha*) populations in the canyons. The Little Colorado River is the home of a significant population of chub, which interact with rainbow trout at the confluence of the Colorado River and the Little Colorado River. Past and proposed methods for encouraging chub population growth involve reducing the number of nonnative trout, which prey on and compete with the chub. Large-scale killing of trout brings Reclamation and NPS into conflict with the value placed on all forms of life held by some Tribes. Although Tribes differ as to whether they consider the removal of nonnative fish species positively or negatively, many Tribes place a high value on the sanctity of life throughout the ecosystem and see themselves as its stewards. For them life, including fish and animal life, must not be wasted and must not be taken except to sustain human life. The Zuni in particular have important cultural ties to aquatic life in the canyons. The confluence of the Colorado River and the Little Colorado River is particularly sacred.

Aquatic resources models allow the comparison of the number of years trout management flows designed to strand trout larvae and fry would be triggered, and the number of years in which mechanical removal of trout would be triggered across the alternatives and their associated long-term strategies. Details of the models are presented in Appendix F.

A trout management flow is a highly variable flow pattern of water releases at Glen Canyon Dam intended to control the number of young-of-the-year trout in the Glen Canyon reach of the Colorado River. Reducing the number of trout in the Glen Canyon reach would reduce the number of trout emigrating downstream to the confluence with the Little Colorado River and other downstream areas. A typical trout management flow would consist of several days of a relatively high sustained flow (e.g., 20,000 cfs) that would prompt young fish to move into the shallows along the channel margins and, depending on the time of year, would prompt spawning fish to construct redds and lay eggs in nearshore shallow areas. The high flows would be followed by a rapid drop to a low flow (e.g., 5,000 cfs), stranding and killing young-of-the-year trout and, depending on the time of year, possibly exposing eggs in shallow redds, thus preventing them from hatching. Management flows would be triggered during years in which the production of young-of-the-year rainbow trout in the Glen Canyon reach is anticipated to be high (more than 200,000 individuals.).

Figure I-5 shows the projected number of years in which trout management flows would be triggered under each alternative and long-term strategy. Trout management flows are not elements of all alternatives and may not occur in many years, even under alternatives that allow them. Under each of the alternatives and long-term strategies in which trout management flows are included, they would first be conducted as tests and then implemented only if they prove to be effective in reducing the trout population in the Glen Canyon reach and emigration to downstream sections of the Colorado River. Trout management flows are not included as elements of nine alternatives/strategies: Alternative C long-term strategies C2, C3, and C4; Alternative D long-term strategy D3; Alternative E long-term strategies E2, E3, E4, and E5; and Alternative F. They would be only tested under Alternative A. In long-term strategies D1, D2, and D4, trout management flow experiments would be implemented without triggers during the first 5 years of the LTEMP period. Figure I-5 assumes experiments in the first 5 years of the LTEMP period. In general, trout management flows would most likely be triggered when spring HFEs, which stimulate the food base, are followed by relatively steady summer flows (May–August). These factors are associated with higher production of young-of-the-year trout and would result in conditions that would trigger trout management flows more often. Where the number of HFEs is limited, as in Alternative B, it is expected that there would be fewer years in which trout management flows would be triggered. Modeling indicates trout management flows would be triggered most often under Alternative G and long-term strategy D2. The mean number of years in which trout management flows would occur are relatively high under long-term strategies D1, D2, and D4 because of the experimental flows that would be implemented, whether trout management flows are triggered or not. If trout management flows prove successful, they would reduce the number of times mechanical removal near the Little Colorado River confluence would be triggered.

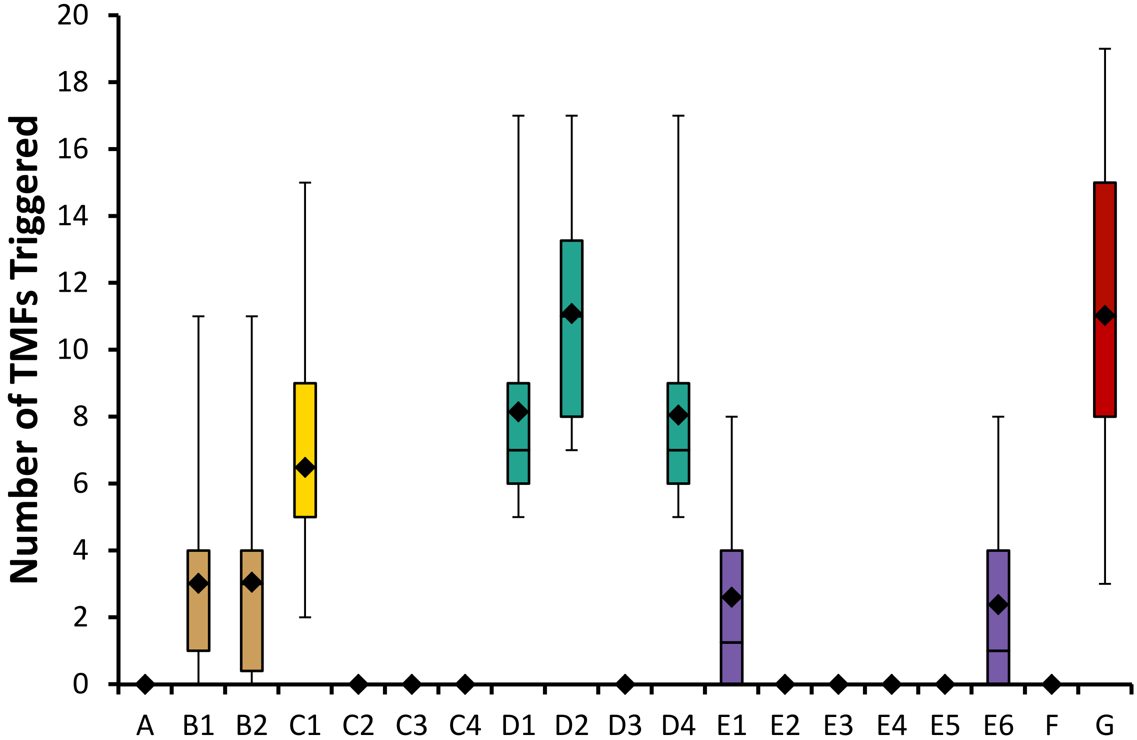

FIGURE I-5 Frequency of Trout Management Flows for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers)

As shown in Figure I-5, trout management flows would be triggered in just under half the alternative long-term strategies. Among the alternative long-term strategies that include trout management flows, the mean number of years during the 20-year LTEMP period in which trout management flows would occur ranges from 2.4 under E6 to 11.0 under Alternative G; the average number ranges between 2 and 4 years under six out of the nine alternative/long-term strategies where trout management flows are allowed.

Figure I-6 shows the frequency of trout management flows under climate change assumptions. A comparison of Figures I-5 and I-6 shows that the frequency distribution pattern is virtually the same for historical and climate change assumptions. On average, the mean value for each alternative/long-term strategy is 0.49 years less under climate change assumptions; this suggests that there would be somewhat fewer trout in the Glen Canyon reach, perhaps a reflection of a drier, warmer future climate.

I.1.4 Mechanical Removal of Trout

Mechanical removal would be implemented by using electrofishing to stun and remove nonnative fish.

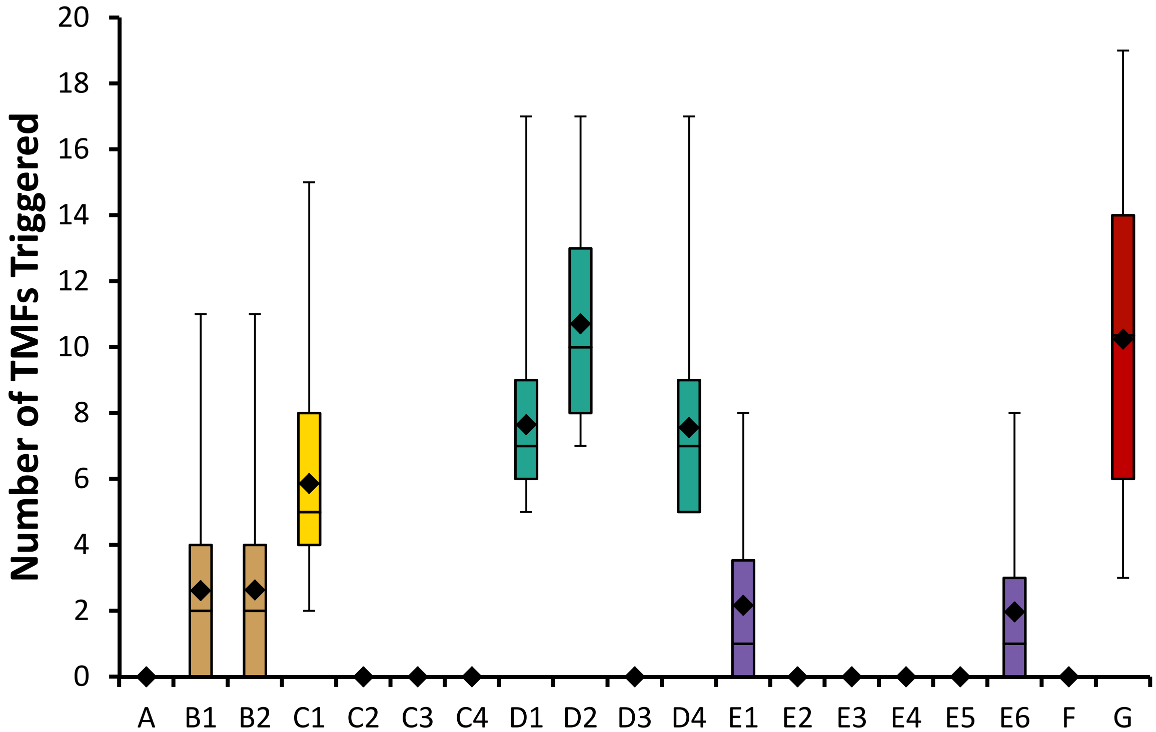

FIGURE I-6 Frequency of Trout Management Flows under Climate Change Assumptions for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers)

Although this does not kill the fish, usually the removed fish would be euthanized (killed) and put to some beneficial use. For example, in one mechanical removal test, the trout were emulsified and used as fertilizer in the Hualapai tribal gardens (Reclamation 2011). Grand Canyon Monitoring and Research Center (GCMRC) has modeled the number of years in which mechanical removal would be triggered under various alternatives. In the model two factors must coincide to trigger mechanical removal trips: (1) there must be more than 760 adult rainbow trout projected for the test reach in the vicinity of the Little Colorado River confluence (RM 63–RM 64.5), and (2) the projected adult humpback chub population for the canyons must be less than 7,000 individuals.

Figure I-7 shows the projected number of years in which mechanical removal from the Little Colorado River reach would be undertaken. Mechanical removal is not an allowed element of seven alternatives/strategies: Alternative C long-term strategies C1 and C2; Alternative E long-term strategies E1, E2, E5, and E6; and Alternative F. The mean number of years in which mechanical removal is modeled to occur ranges from 0.07 under Alternative A to 3.05 under Alternative G. In general, mechanical removal would be triggered in far fewer years than trout management flows. Modeling indicates that the average maximum number of years in which mechanical removal would be triggered is 6.3 out of 20, the projected maximum under D3. The overall pattern of mechanical removal events would be similar to the pattern of trout management flow occurrences and for similar reasons. Conditions that favor trout production

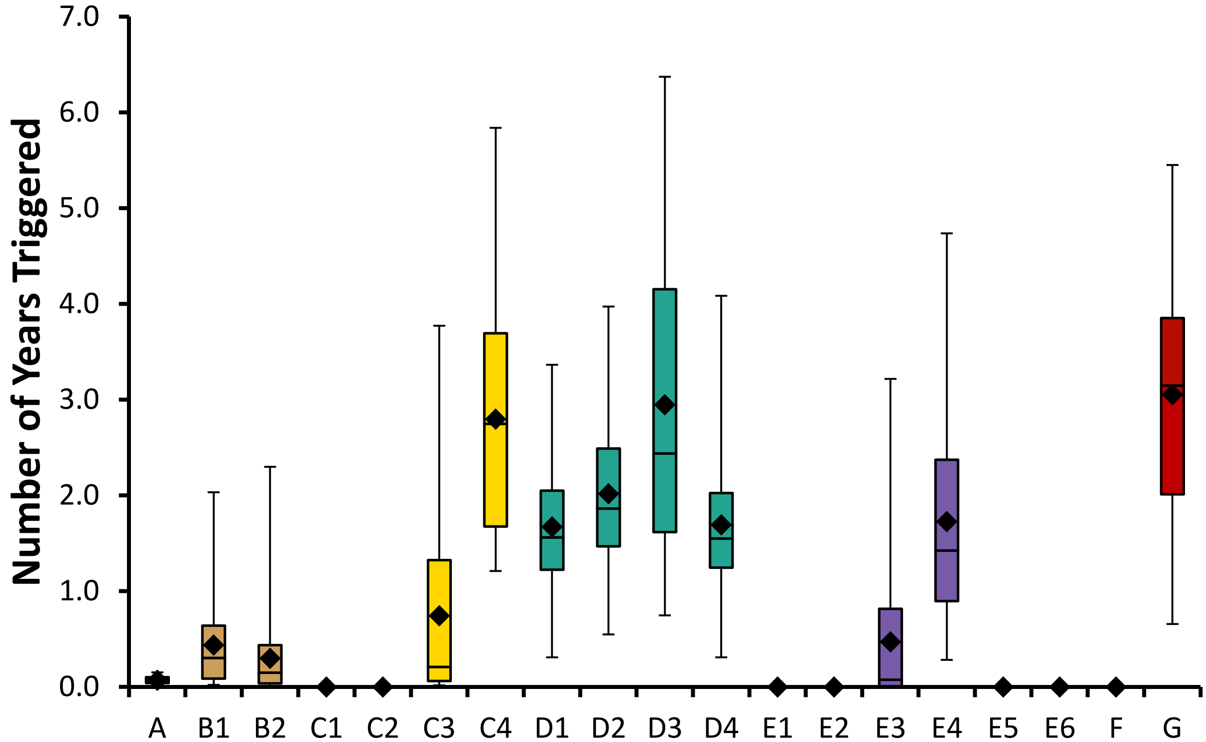

FIGURE I-7 Frequency of Mechanical Removal for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers)

(spring HFEs and steady summer flows) result in trout population increases in the Glen Canyon reach, thereby increasing the number of trout that move downstream to the Little Colorado River reach and triggering mechanical removal more often.

Figure I-8 shows the frequency of mechanical removal under climate change assumptions. As with trout management flows, the distribution pattern varies very little between the two plots. In all cases except Alternative G there is a slight decline in the mean number of years in which mechanical removal would be triggered. On average, those that score lower under climate change assumptions score 0.13 years less, while Alternative G scores 0.06 years more. This suggests that with the exception of Alternative G, river conditions would be slightly less favorable for trout production under climate change conditions.

I.1.5 Water Levels at Lake Powell

The domestic water supply for the LeChee Chapter of the Navajo Nation is obtained from Lake Powell through pumping and conveyance facilities that were first constructed at the time Glen Canyon Dam was built between 1957 and 1964 (NPS 2009). The current system relies on either an intake on the face of the dam at 3,480 ft above mean sea level (AMSL), or an intake off the penstocks, which are at an elevation of 3,470 ft AMSL at Lake Powell. Therefore, 3,470 ft

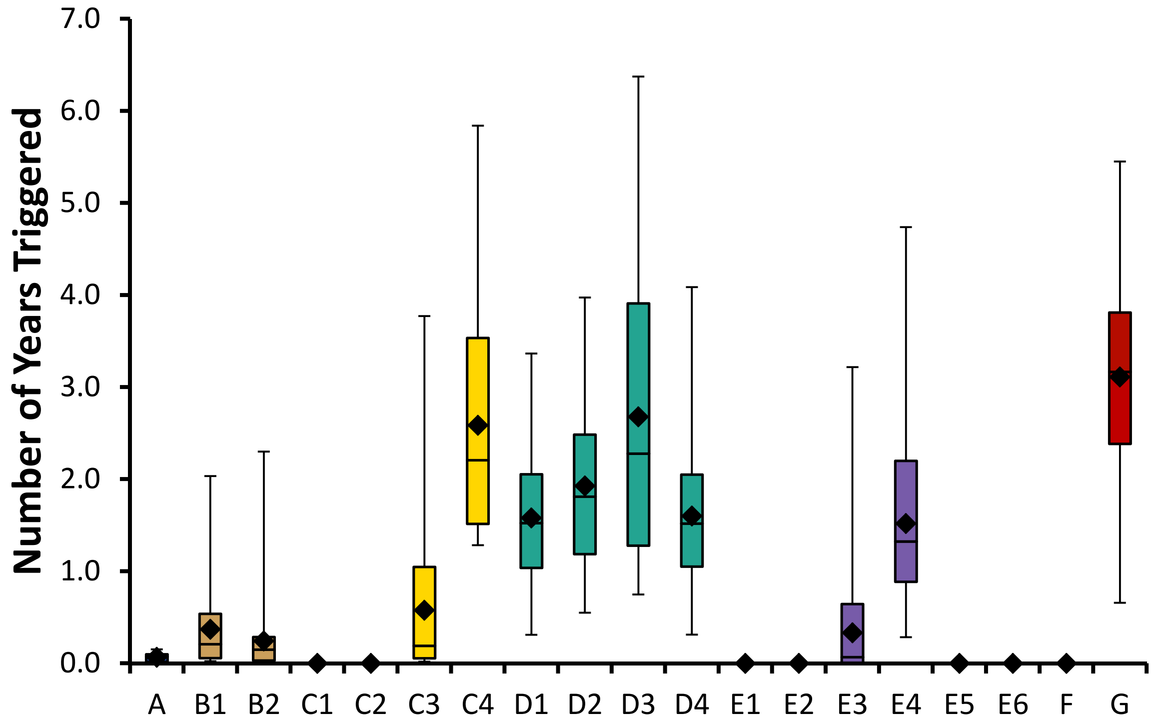

FIGURE I-8 Frequency of Mechanical Removal under Climate Change Assumptions for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers)

AMSL is the minimum elevation necessary for the LeChee Chapter to draw water from Lake Powell, even while penstock units are down or are undergoing maintenance.

An environmental assessment (EA) done in 2009 addresses possible future construction to provide a backup water supply to the area (NPS 2009). Three designs for new water supply systems from Lake Powell for the City of Page and the LeChee Chapter were evaluated. The EA eliminated two of the designs and narrowed the options to either no action or an entirely new pumping system which calls for six 48-in. intake pipes reaching the lake at an elevation of 3,373 ft AMSL.

The Colorado River Simulation System (CRSS) model was used for the LTEMP process to project future river and reservoir system conditions on a monthly time-step.

Because there are no known restrictions within the model for the intake pipes, an analysis was conducted to identify modeled minimum Lake Powell elevations in order to address concern regarding the LeChee Chapter's ability to draw water under LTEMP. End-of-the-month Lake Powell elevations were created as part of the LTEMP analysis (see Appendix E) for all the different hydrologic and sediment inputs (see Section 4.1 for a presentation of the overall modeling approach). A script within the MATLAB® scripting program was created to retrieve the minimum elevation possible within each alternative.

As shown in Figure I-9, there is little variation projected for Lake Powell water levels among the LTEMP alternatives. The mean water level for Lake Powell under all alternatives and long-term assumptions falls between 3,540 ft AMSL and 3,560 ft AMSL, well above intake elevations. More importantly, the minimum elevation of the lake modeled for all different input combinations and alternatives was 3,480 ft AMSL. This is the same elevation as the intake on the dam face and 10 ft above the elevation of the penstock intakes and well above elevations for any planned future intakes. Although there is always potential for modification of dam operations based on circumstantial conditions, the LeChee Chapter is projected to retain its water supply from Lake Powell under all LTEMP alternatives, with average levels slightly higher under Alternative F than the other alternatives.

As seen in Figure I-10, with the exception of Alternative F, climate change assumptions mean lake elevations are projected to fall just below 3,540 ft AMSL. Mean lake levels under Alternative F would be just above 3,540 ft AMSL. Even under climate change assumptions, minimum lake elevations are never projected to fall below 3,480 ft AMSL and are project to remain at least 10 ft above the minimum required to supply the LeChee Chapter with water. Only under Alternative F would the minimum projected Lake Powell elevation be above 3,490 ft AMSL.

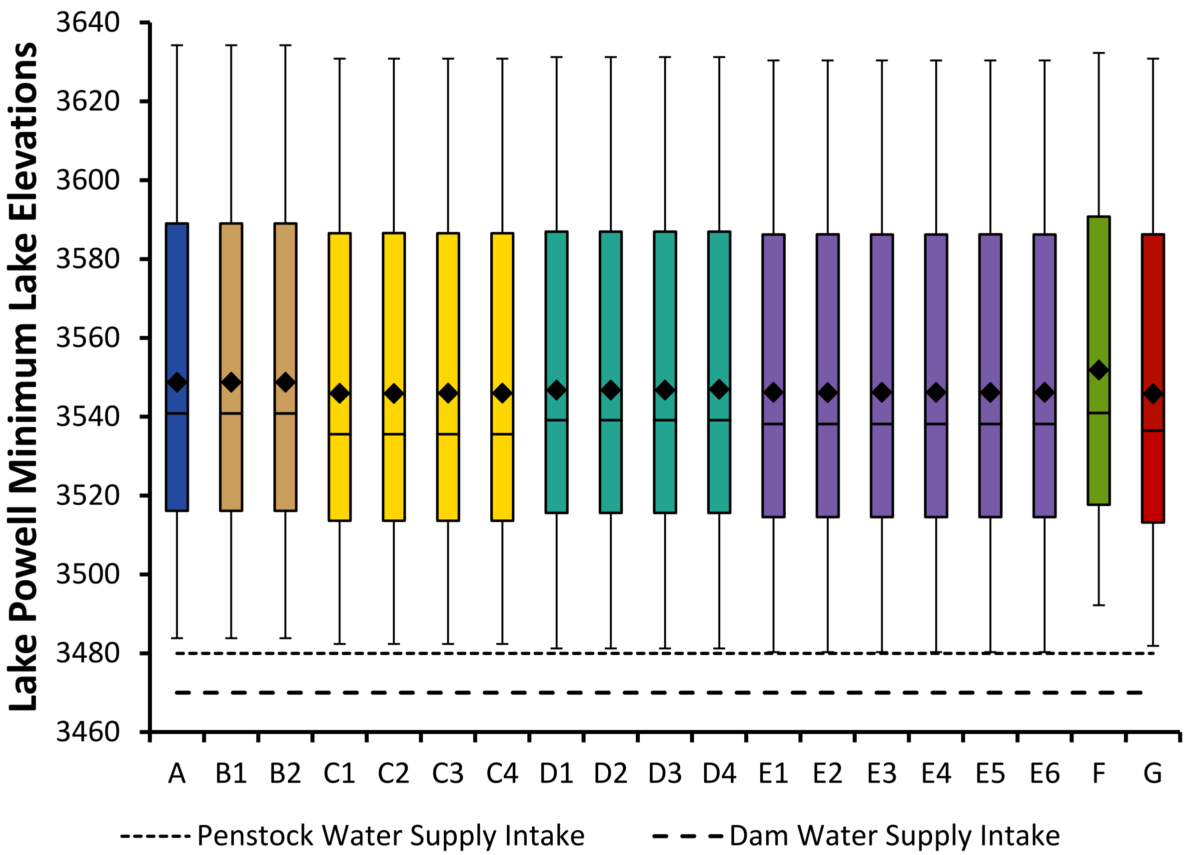

FIGURE I-9 Lake Powell Water Levels for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers)

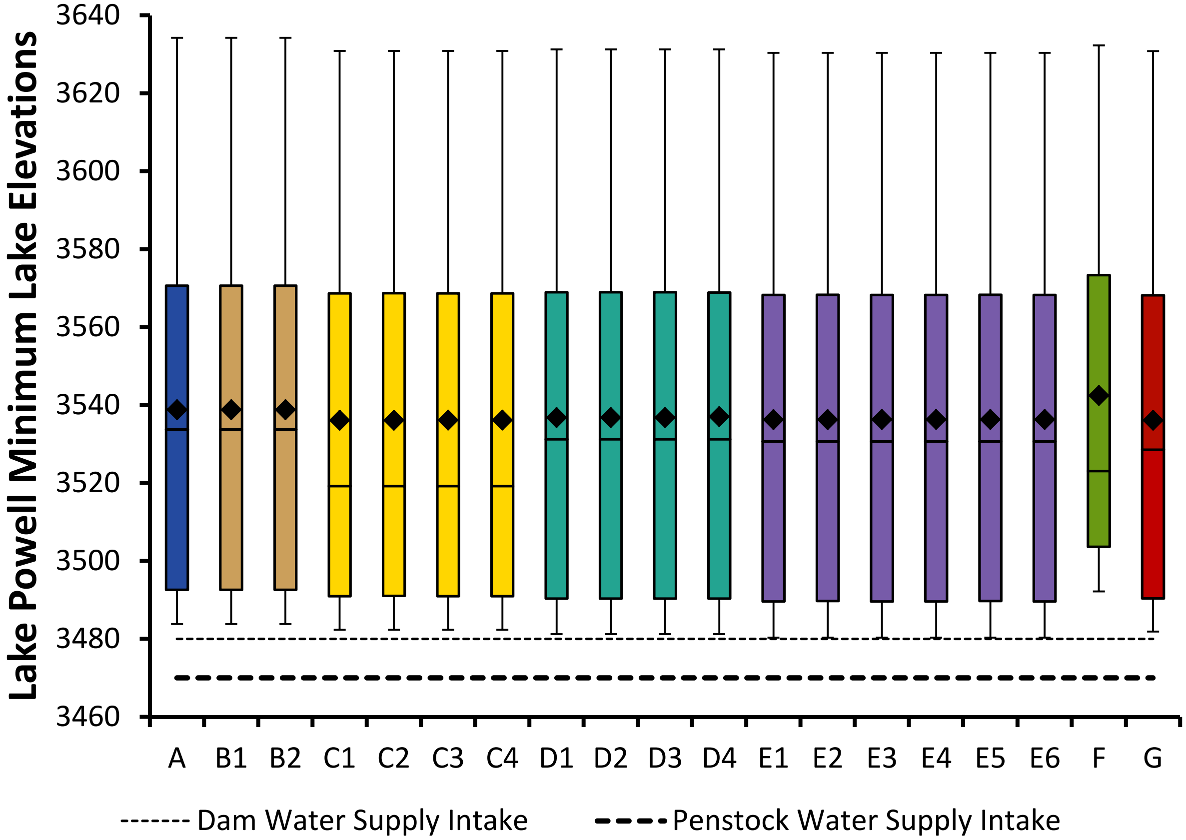

FIGURE I-10 Lake Powell Water Levels under Climate Change Assumptions for the LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers)

I.1.6 Access to Resources

Access to culturally important sites and resources has the potential to be a significant factor in assessing impacts from the alternatives. Resources important to the Tribes include plant resources important for food, medicinal, and ritual purposes; minerals including salt and pigments that are ritually important; and sacred places including springs and offering sites. Potential access interruption is tied to the frequency of HFEs. HFEs could cause temporary loss of access to culturally important resources through inundation of the resources or trails leading to them. These temporary interruptions can be mitigated by communication between Reclamation and the Tribes so that Tribes have notice of impending HFEs. Of the LTEMP alternatives, Alternative F and Alternative G have the most HFEs. Under the latter alternative, there are HFEs that last as long as 2 weeks. Alternative C long-term strategies C1 and C2 have a similar number of HFEs as the steady flow alternatives. Alternative C long-term strategy C4 and Alternative E long-term strategies E1, E2, and E4 have a moderate number of HFEs. Alternative A and Alternative B long-term strategies are projected to have a small number of HFEs (seven or fewer over 20 years). No HFEs are projected for Alternative C long-term strategy C3 or Alternative E long-term strategies E3, E5, and E6.

Potential impacts on archeological sites important to Tribes are discussed in technical Appendix H.

I.2 REFERENCES

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APPENDIX J:

RECREATION, VISITOR USE, AND EXPERIENCE TECHNICAL INFORMATION AND ANALYSIS

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APPENDIX J:

RECREATION, VISITOR USE, AND EXPERIENCE TECHNICAL INFORMATION AND ANALYSIS

The Glen and Grand Canyons of northern Arizona provide a unique experience of extraordinary geologic landscapes, diverse wildlife and vegetation, and over 12,000 years of human history for visitors from across the globe. The area offers a variety of recreational activities including flatwater and whitewater boating, hiking, and angling. This Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) Draft Environmental Impact Statement (DEIS), developed by the Bureau of Reclamation (Reclamation) and the National Park Service (NPS), has identified the recreational experience goal as being to "maintain and improve the quality of recreational experiences for the users of the Colorado River ecosystem. Recreation includes, but is not limited to, flatwater and whitewater boating, river corridor camping, and angling in Glen Canyon" (Section 1.4). Past recreational studies have shown that Glen Canyon Dam operations can affect the experience of recreationalists in the downstream Glen and Grand Canyons (Bishop et al. 1987; Hall and Shelby 2000; Stewart et al. 2000; Roberts and Bieri 2001). In an effort to quantitatively assess the downstream impacts on recreational activities of the LTEMP alternatives, six performance metrics were created to address recreational concerns. This appendix explains the metrics and compares the performance of the LTEMP alternatives as indicated by the metrics.

The alternatives encompass 19 long-term strategies, which include various combinations of experimental components (Appendix C). A full range of potential hydrologic and sediment conditions were modeled for the 20-year LTEMP period. Twenty-one potential Lake Powell in-flow scenarios (known as hydrology traces) for the 20-year LTEMP period were used to generate twenty-one 20-year hourly release patterns for each alternative and long-term strategy. In addition to these twenty-one hydrology traces, three 20-year sequences of sediment inputs from the Paria River sediment record were analyzed that represented low, medium, and high sediment conditions. In combination, the twenty-one hydrology traces and three sediment traces resulted in an analysis that considered sixty-three possible hydrology-sediment conditions.

In the presentation of results below, LTEMP alternatives are identified by the alternative letter designation (Alternatives A through G) and, if the alternative includes multiple long-term strategies, a number designation (1 through 6, depending on the number of long-term strategies for an alternative) that denotes a particular long-term strategy within an alternative. See Appendix C for descriptions of the long-term strategies.

J.1 RECREATIONAL EXPERIENCE METRICS

The analysis of potential impacts on recreational experience is based primarily on the evaluation of six quantitative metrics that were developed for the assessment, but also on more qualitative information and experience of GCNRA and GCNP staff and on the studies that served as the basis for quantitative metrics. The metrics were developed through consultation with subject matter experts, findings in published papers and reports, and with consideration of comments from the Cooperating Agencies.

J.1.1 Grand Canyon Metrics

Of the six evaluation metrics, four address issues important to visitor use and experience in Grand Canyon National Park (GCNP) downstream of Lees Ferry, while the remaining two metrics address the Glen Canyon reach between the dam and Lees Ferry. The metrics are:

- *Camping Area Index:* Accounts for optimal campsite area building and maintenance flows and sediment load (also used as input to the assessment of campsite crowding).

- *Navigational Risk Index:* Measure of navigation difficulty based on the number of days during which the daily minimum flow was less than 8,000 cfs (also used as input to the assessment of campsite crowding and encounters with other groups).

- *Fluctuation Index:* Measures the degree to which combinations of flows and fluctuations are within a range identified as preferable by experienced boat guides.

- *Time Off River Index:* Relates the level of flows to visitors being able to spend time ashore visiting attractions.

J.1.2 Glen Canyon Metrics

- *Glen Canyon Rafting Metric:* Estimates the number of visitors unable to participate in day rafting in Glen Canyon due to high flows.

- *Glen Canyon Inundation Metric:* Accounts for flows that impact recreational sites and recreational uses within the Glen Canyon reach.

Some of the metrics evaluate non-tangible, qualitative aspects of the recreational experience. Such metrics may be based on results of recreational surveys of visitor experience under various flow and fluctuation conditions, which overlap dam operations under LTEMP alternatives (Hjerpe and Kim 2001). These and other metrics used in the analyses and described elsewhere in this DEIS (see Appendices B and C) based on relative performance are expressed as an index having values from 0 to 1, where increasing values indicate increasing performance with respect to the associated resource goal. Metrics employing an index include the Camping Area Index (CAI), Navigational Risk Index (NRI), the Fluctuation Index (FI), the Time Off River Index (TORI), and the Glen Canyon Inundation Metric (GCIM). The Glen Canyon Rafting Metric (GCRM) is the only metric that uses an absolute scale. It is the number of potential lost visitor trips for day-use rafts in Glen Canyon due to high flows during high-flow experiments (HFEs).

The metrics all rely on the hourly Glen Canyon Dam discharge computed by the GTMax-Lite model (Reclamation 2007) with the incorporation of a sediment analysis (Russell and Huang 2010) to account for HFE implementation (Appendix E). GTMax-Lite produces a trace (20 years of hourly discharge) for each combination of hydrology and tributary sediment traces input into the model. For each metric, all 7 alternatives and any associated long-term strategies were analyzed for all 63 traces (see Section 4.1 for more detail). The following sections explain the calculation of recreation metrics for an individual trace.

In all metrics but the GCRM, the index value is weighted to emphasize seasons with greater recreational use over the course of a year. Percent of annual recreation use was determined to be 15% in the winter months of November, December, January, and February; 31% in the spring and fall months of March, April, September, and October; and 54% in the summer months of May, June, July, and August (based on monthly visitation statistics presented in https://irma.nps.gov/Stats/Reports/Park/GRCA).

J.2 METRIC DEFINITIONS, ANALYSIS METHODS, AND RESULTS

J.2.1 Camping Area Index

Campsites are primarily located on sandbars along the shoreline of the river, and they provide open, flat areas ideal for camping. Crucial for multi-day trips, campsites can limit the visiting capacity (the number of people to maintain a desired natural visitor experience) for high-demand downstream rafting trips (Kearsley et al. 1994). The management of campsites is therefore of particular concern to river managers (NPS 2006). To meet the visitor capacities established in the NPS Colorado River Management Plan, it is necessary to develop and retain medium (16–25 people) and large (>25 people) campsites, which maintain and potentially improve visitor experience based on preferences expressed in surveys of visitors. Commercial and private trip leaders preferred large beaches for camping compared to smaller beaches (Stewart 2000). A study by Kaplinski and others monitoring campsites from 1998 to 2012 reported a decrease of average campsite area by 36% with any decrease in area noted at 29 out of the 37 study sites (Kaplinski et al. 2014).

Dam operations have been shown to have significant effects on campsite area. HFEs have proven to temporarily increase campsite area due to sandbar deposition (Grams et al. 2010; Hazel et al. 2010). In the Grand Canyon Monitoring and Research Center (GCMRC) *Fiscal Year 2014 Annual Project Report* (GCMRC 2015), Kaplinski and others concluded, “sandbar deposition associated with high flows results in increases in campsite area, while post-HFE erosion causes decreases in campsite area.” Currently, it is perceived that lower discharge reduces erosion to campsites, while also exposing campsites that are covered at higher discharges. A decrease of discharge from 25,000 cfs to 15,000 cfs during normal flows increased campable area by 73%; a further increase of 46% in campable area was seen when discharges further decreased to 8,000 cfs (Kearsley and Warren 1993).

J.2.1.1 Camping Area Index—Methods

The Camping Area Index (CAI) evaluates the conditions conducive to increased camping area in the Grand Canyon, which is a function of the amount of sand deposited and retained and campsite area exposure as a function of river level (flow rate). The output from the Sand Load Index (SLI), which simulates sediment conditions between RM 0 and 30 provides a proxy for indicating whether the alternatives are likely to create the conditions conducive to creating/retaining campsite area (Appendix E). The CAI is the product of the SLI and a Seasonally Weighted Flow Factor (SWFF):

$$CAI = Average(SWFF)_{2014-2033} \times SLI$$

Both the SLI and SWFF are indices ranging from 0 to 1, as is the resulting CAI, where a value of 1 indicates the greatest potential to increase camping area. As the metric output is a generalization of sediment conditions throughout the canyon, it does not predict conditions at any particular site. Erosion is not taken into account in the CAI. Daily flow level is accounted for in the SWFF, as discussed below. Lower flows provide more camping area (i.e., there is more camping area at 8,000 cfs than at 25,000 cfs because more sand is exposed at lower flows [Kearsley and Warren 1993]). The minimum flow within the daytime period (7 am to 7 pm) is 8,000 cfs under most LTEMP alternatives.

The SLI is an index of the potential sand deposited on sandbars along the river channel in Marble and Grand Canyons above normal stage elevations (31,500 cfs). The SLI is calculated as the ratio of the cumulative sand load at flows greater than 31,500 cfs relative to the total cumulative sand load at all flows modeled (Appendix E). The sand load, or the mass of sand in transport by the river, is calculated at RM 30 and is computed by a version of the Sand Budget Model (Wright et al. 2010) for the 20-year LTEMP period. A larger SLI (on a scale of 0–1), indicates a greater potential for sediment deposition. The SLI was calculated using the following equation:

$$SLI = \frac{\sum_{2014-2033} Sand\ Load\ at\ dam\ discharges > 31{,}500\ cfs}{\sum_{2014-2033} Sand\ Load\ at\ all\ dam\ discharges}$$

The SWFF is a yearly value representing the relative amount of river bank exposure available for camping areas dependent on the Glen Canyon discharge. Low river flows will expose more campsite area while higher flows will submerge campsite area and potentially cause erosion (Kearsley and Warren 1993). Flows above 8,000 cfs are considered to increasingly reduce camping area and to submerge most campsite areas at 31,500 cfs. Camps above 25,000 cfs are considered high campsites in Kaplinski (2014). With no data on the exact location of all campsites relative to the river, an informed assumption is made here. The daily maximum flow is used to evaluate the extent to which flows may cover campsites at any point in the day.

Modeled daily flows are assigned a 0–1 index value, referred to as the daily flow factor (FF_{Daily}):

$$FF_{Daily} = \begin{Bmatrix} \text{if } Q_{max} \leq 8{,}000 \text{ cfs}; & 1 \\ \text{if } 8{,}000 < Q_{max} < 31{,}500\ cfs; & 1.34 - 0.0000425 \times Q_{max} \\ \text{if } Q_{max} \geq 31{,}500 \text{ cfs}; & 0 \end{Bmatrix}$$

where Q_{max} refers to the daily maximum discharge released from the Glen Canyon Dam in cfs and FF_{Daily} is equal to the value in the right column if the equation in the left column is satisfied.

The yearly index value (SWFF) is the ratio of the index values for each season:

$$\text{SWFF} = \left\{0.15\left(\frac{\sum_{\text{winter}} FF_{daily}}{\sum Days_{winter}}\right) + 0.31\left(\frac{\sum_{\text{spring}\&fall} FF_{daily}}{\sum Days_{spring\&fall}}\right) + 0.54\left(\frac{\sum_{\text{summer}} FF_{daily}}{\sum Days_{summer}}\right)\right\}$$

J.2.1.2 Camping Area Index—Results

CAI values for all 19 LTEMP long-term strategies are shown in Figure J-1. All of these have higher CAI values than Alternative A (no-action alternative). Long-term strategies B2, C3, E3, E5, and E6 rank below Alternative A. With the exception of B2, HFEs are not conducted for these long-term strategies, and therefore flows above 31,500 cfs, the primary mechanism for sediment deposition, occur rarely, if at all. Experimentally increased flow fluctuations (hydropower improvement flows) under B2 cause it to rank below Alternative A.

The CAI is fairly insensitive to SWFF because SWFF values typically range only between 0.55 and 0.77. Consequently, the CAI is strongly dependent on the SLI, and therefore to the number of HFEs under a given alternative or long-term strategy (see Appendix E). The strong dependence of CAI on SLI can be seen by comparing Figure J-1 and Figure J-2.

Alternative G has the highest CAI, a value 3.2 times that of Alternative A. This result is attributed to the highest number of HFEs and relatively even year-round daily flows under Alternative G, conditions conducive to conserving sediment and increasing camping area through deposition and retention of sediment. Ranking second-highest, Alternative F, with a CAI 2.9 times that of Alternative A, has low flows in non-summer months and more 96-hour HFEs than other long-term strategies.

Long-term strategy B2 has a slightly reduced CAI compared to B1 attributable to testing of hydropower improvement flows under B2, which reduces CAI through reductions in both SLI and SWFF. The CAI for long-term strategy C4 is reduced relative to that for C1 and C2 due to the absence of spring HFEs and proactive spring HFEs under C4, which reduces its SLI value. C3 is much reduced owing to the absence of spring or fall HFEs, as noted above.

The CAI for long-term strategy D4 is not significantly different from D1, D2, D3, or C1, based on a test of differences between means using a three-factor analysis of variation (ANOVA)

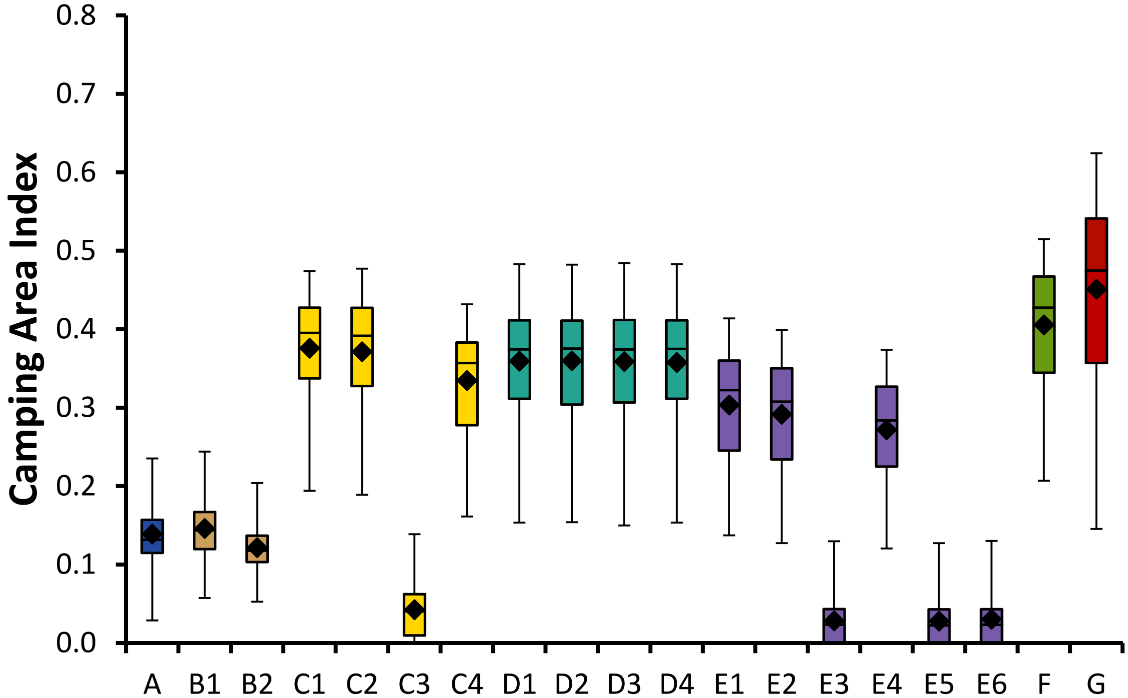

FIGURE J-1 Camping Area Index for LTEMP Long-Term Strategies (Increasing values indicate increasing camping area. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum.)

followed by Tukey's Studentized Range Test. This indicates that low summer flows under D1, D2, and D3 have no effect on CAI, nor does sustained low flows for benthic invertebrate production under D2 or the absence of trout management flows under D3.

The CAI for long-term strategy E4 is slightly lower than that for E1 and E2, indicating a small reduction in sediment retention for E4 due to the absence of spring HFEs in the second 10 years of the LTEMP period, which are conducted under E1 and E2. As noted above, E3, E5, and E6 do not include spring or fall HFEs, explaining their low CAI values.

J.2.2 Navigational Risk Index

Navigating the Colorado River downstream of Glen Canyon Dam at low flows, especially at rapids, can cause difficulties for oar and motor trips. A survey conducted by Bishop et al. (1987) of commercial oar and motor guides indicated that flow levels below 9,200 cfs and 8,400 cfs, respectively, began to compromise boater safety. In the Bishop et al. (1987) study, guides were simply asked for minimum levels of flow for running safely with passengers. Survey respondents noted that at these flows, boat accidents related to exposed rocks are much more probable. A similar survey by Shelby et al. (1992) reported nearly the same

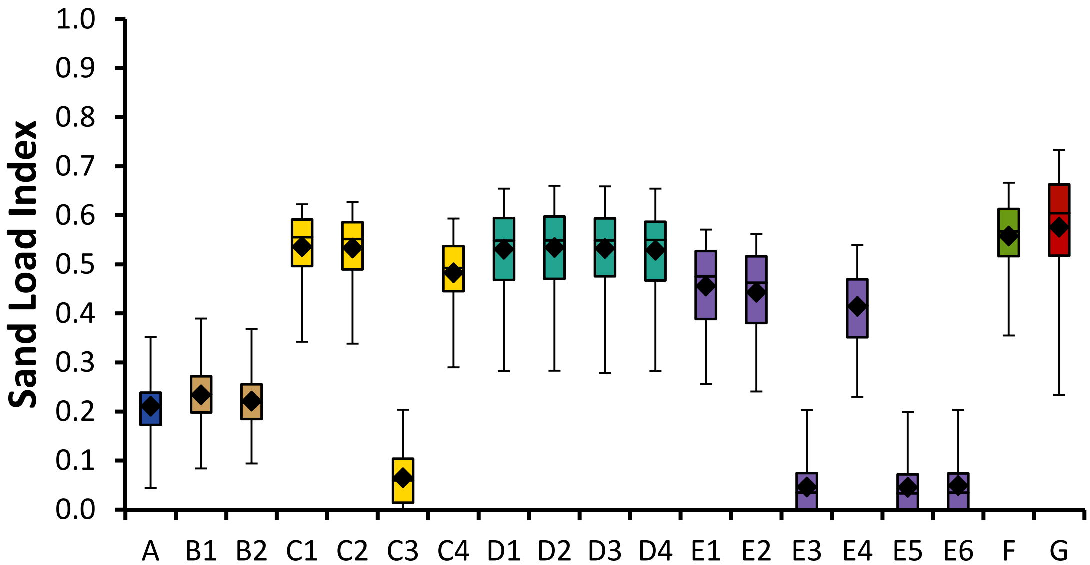

FIGURE J-2 Sand Load Index (see Appendix E) for LTEMP Long-Term Strategies (Increasing values indicate more sediment deposited along river banks. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum.)

values as Bishop et al. (1987), and a more recent survey by Stewart et al. (2000) had similar findings with oar and motor river guides identifying approximately 8,100 cfs and 7,800 cfs, respectively, as minimum flows for what they considered safe river trips. Exposures to experimental low flows of 8,000 cfs in the summer of 2000 further supported the guides' perceptions of potentially dangerous flows, with double the number of boating accidents reported than the previous year, mostly associated with hitting exposed rocks (Ralston 2011).

J.2.2.1 Navigational Risk Index—Methods

To assess the risk due to difficulties of motor rigs navigating rapids at lower flows, the risk (frequency) of daily minimum discharges that are ≤8,000 cfs was determined for each season. To account for the variance in use between the seasons, the yearly value is averaged with weights corresponding to recreational use as used above for SWFF in calculating the CAI. The annual risk was calculated as:

$$Risk = \left\{0.15\left(\frac{\sum_{\text{winter}} Days_{min}}{\sum Days_{winter}}\right) + 0.31\left(\frac{\sum_{\frac{\text{spring}}{\text{fall}}} Days_{min}}{\sum Days_{\frac{spring}{fall}}}\right) + 0.54\left(\frac{\sum_{\text{summer}} Days_{min}}{\sum Days_{summer}}\right)\right\}$$

where $Days_{min}$ is the number of days when flows were <8,000 cfs, $Days_{winter}$ is the number of days in the winter, $Days_{spring/fall}$ is the number of days in the spring and fall, and $Days_{summer}$ is the number of days in the summer.

The index is the complement of the risk, where 1 indicates 100% of minimum daily flow above 8,000 cfs and is therefore the least risk to river navigators. Thus, the NRI for a single input trace for the LTEMP period of 2014–2033 is as follows:

$$NRI = Average(1 - Risk)_{2014-2033}$$

While Alternatives A through E restrict minimum flows to 8,000 cfs during day hours (7 am to 7 pm), flows during night hours (7 pm to 7 am) can drop to 5,000 cfs, and these low flows can affect downstream boaters during daylight hours well after the change in discharge rate occurs at the dam due to the transit time required for the change to reach downstream locations. The calculation of daily minimum flow was therefore inclusive of the entire 24-hour period.

J.2.2.2 Navigational Risk Index—Results

NRI values for each alternative are shown in Figure J-3. Long-term strategies C1–C4, D2, F, and G have higher values than Alternative A, while D1, D3, and D4 are only slightly lower than Alternative A. Long-term strategy B2 has the lowest NRI value owing to high flow fluctuations and low minimum flows, while B1 and E1–E6 are also lower than Alternative A.

Alternative G has year-round steady flows of approximately 11,000 to 13,000 cfs, rarely dipping below 8,000 cfs, resulting in an NRI approaching 1 (lowest risk). Alternative F, which also has steady daily flows, has high flows in the months of February through June and lower flows running near or below 8,000 cfs in July through January. However, for the historic water volumes modeled (typically greater than 8.23 maf), higher releases would sometimes occur for equalization purposes at the end of the water year. Primarily for this reason, the average days with flows above 8,000 cfs actually outnumber the days below it for Alternative F. On average, Alternative F has an NRI almost 1.5 times that of Alternative A.

For alternatives with fluctuating flows, the size of daily fluctuations generally differentiates between alternatives, while experimental features drive differences between long-term strategies within alternatives. Daily fluctuations under Alternative C are lower than those under Alternatives A, D, E, and B, resulting in fewest occurrences of flows less than 8,000 cfs and the highest NRI value (lowest risk) of the fluctuating-flow alternatives. The relative ranking of these alternatives in Figure J-3 generally reflects the size of daily fluctuations, which determines the frequency of flows less than 8,000 cfs.

Within alternatives, long-term strategy B2 has a lower NRI (higher risk) than B1 due to high fluctuations and flows less than 8,000 cfs associated with experimental hydropower improvement flows not included in B1. For the same reasons, B2 has the lowest NRI (highest risk) of all long-term strategies. C2 has a slightly lower NRI than C1, C3, and C4 due to the

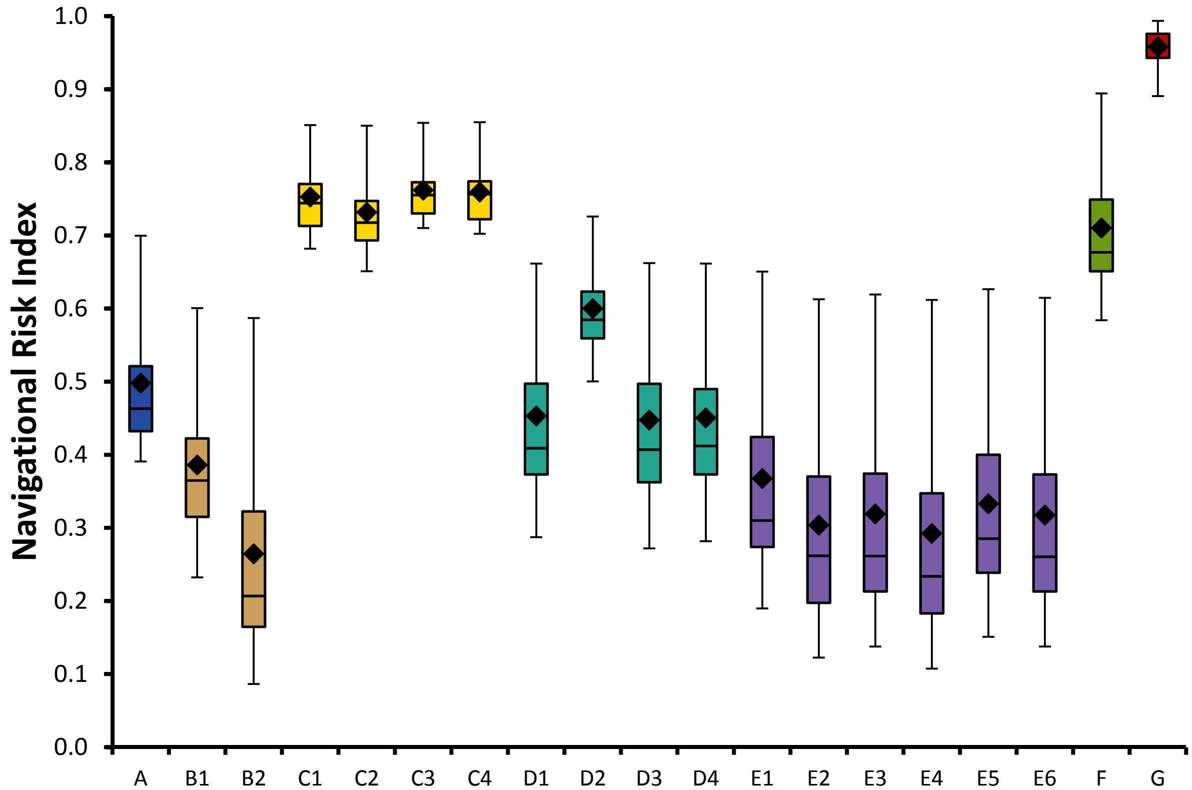

FIGURE J-3 Navigational Risk Index Values for the LTEMP Long-Term Strategies (Increasing values indicate improving navigation conditions. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum.)

inclusion of low summer flows, which allows minimum daily flows as low as 5,000 cfs. Low weekend flows to promote benthic invertebrate production during May–August under long-term strategy D2 increase the overall minimum flow during those months, elevating the NRI relative to D1, D3, and D4. Absence of low summer flows under E1, E3, E4, and E6 elevates the NRI for these long-term strategies slightly compared to E2 and E5.

J.2.3 Fluctuation Index

Whitewater rafting guides surveyed by Bishop et al. (1987) indicated that moderate (8,000–25,000 cfs) and severe (1,000–33,500 cfs) daily fluctuations are potentially problematic for rafting trips. Fluctuations can complicate mooring at campsites, and running rapids, and can increase the unpredictability of flows. Bishop et al. surveyed guides and private trip leaders with experiences of both large fluctuations (greater than 15,000 cfs) and steady flows and documented the ranges of tolerable fluctuations at various river flow levels, as shown in Table J-1.

TABLE J-1 Reported Mean Tolerable Daily Changes in Flow Levels for Commercial Motor Guides, Commercial Oar Guides, and Private Trip Leaders[a]

River flow (cfs)	Tolerable Fluctuations (cfs)
5,000–8,999	2,400–*3,400*[b]
9,000–15,999	3,900–*4,800*
16,000–31,999	6,400–*7,200*
32,000 and up	7,900–*9,800*

[a] Table modified from Table 4-7 of Bishop et al. 1987.

[b] Italicized values indicate the maximum tolerable fluctuation threshold used in the Fluctuation Index.

J.2.3.1 Fluctuation Index—Methods

Table J-1 is the basis for the Fluctuation Index (FI). It is assumed that (1) the river flow ranges shown in the left-hand column of Table J-1 are based on the mean daily flow and that (2) the maximum tolerable fluctuation threshold (italicized flow values in Table J-1) serves as the level above which fluctuations become increasingly more unacceptable to river users.

A daily flow factor (FF) value of 0–1 was computed using Table J-1 and the mean flow for a given day. The daily flow factor is 1 if the fluctuations are within the acceptable range. Above the threshold, daily FF goes linearly to zero as the fluctuation increases to 10,000 cfs. Daily fluctuation levels greater than 10,000 cfs are clearly noticeable and have strong adverse effects on river users (Bishop et al. 1987). The daily FF is computed as follows, where Q_{avg} is the daily mean flow, Q_{range} is the daily fluctuation, and Q_{tol} is the tolerable fluctuation threshold:

$$FF_{daily} = \left\{ \begin{array}{ll} \text{if } Q_{range} \leq \quad Q_{tol} & 1 \\ \text{if } Q_{range} > \quad Q_{tol} & \\ \quad where\ 5{,}000 < Q_{avg} < 8{,}999 & 1.515 - (0.00015 \text{ x } Q_{range}) \\ \quad where\ 9{,}000 < Q_{avg} < 15{,}999 & 1.923 - (0.00019 \text{ x } Q_{range}) \\ \quad where\ 16{,}000 < Q_{avg} < 31{,}999 & 3.571 - (0.00036 \text{ x } Q_{range}) \\ \quad where\ Q_{avg} > 32{,}000 & 50 - (0.005 \text{ x } Q_{range}) \end{array} \right\}$$

The annual FI is the sum of daily FFs weighted by season according to recreational use, with seasonal weights being the same as for the NRI:

$$FI_{annual} = \left\{0.15\left(\frac{\sum_{winter} FF_{Daily}}{\sum Days_{winter}}\right) + 0.31\left(\frac{\sum_{spring/fall} FF_{Daily}}{\sum Days_{spring/fall}}\right) + 0.54\left(\frac{\sum_{summer} FF_{Daily}}{\sum Days_{summer}}\right)\right\}$$

An overall annual mean index value for the 20-year modeling period was calculated as follows:

$$FI = Average\ (FI_{annual})_{2014-2033}$$

J.2.3.2 Fluctuation Index—Results

The results of the FI are shown in Figure J-4. Differences between alternatives reflect differences in levels of daily flow fluctuations under the respective operational regimes. Alternatives F and G have FIs approaching 1 due to the absence of daily fluctuations; G is slightly lower, as it includes trout management flows in years when trout recruitment is high. Alternatives C, A, D, E, and B have rankings in order of increasing levels of daily fluctuations.

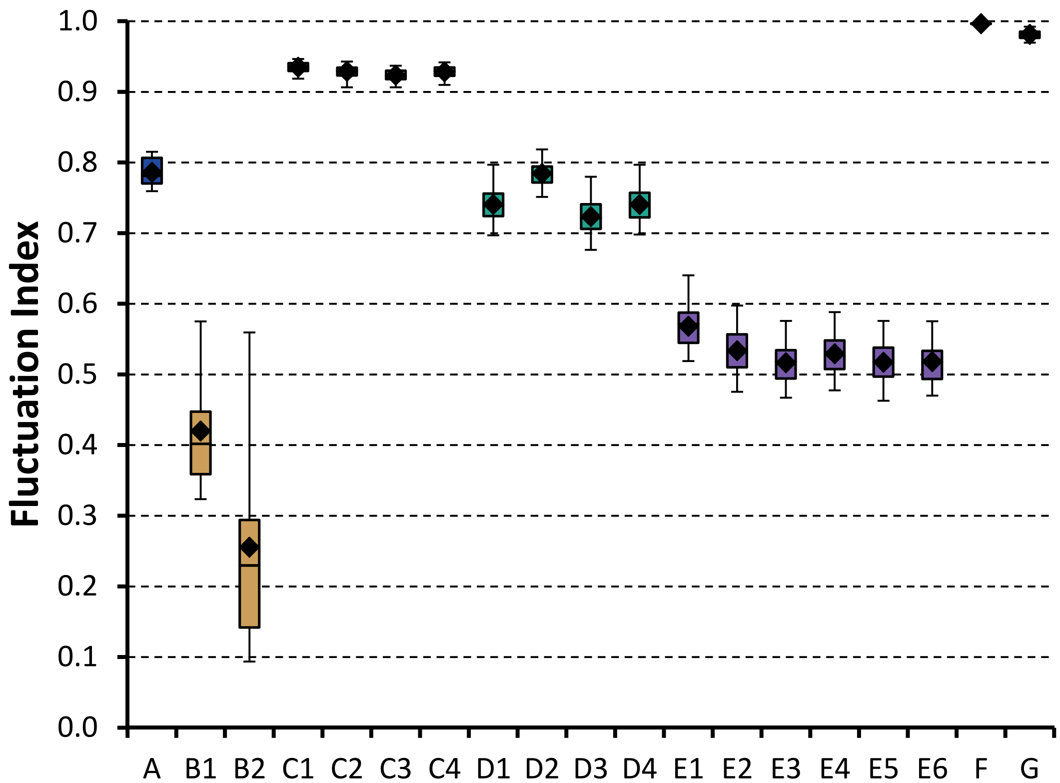

FIGURE J-4 Fluctuation Index for LTEMP Long-Term Strategies (Increasing values indicate more days have tolerable fluctuation levels. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum.)

Alternative A and all long-term strategies under Alternatives C, D, and E have average index values above 0.5, indicating a high proportion of daily fluctuations that are within the tolerable range. Long-term strategy B1 has an annual FI value roughly half that of Alternative A, while B2 has a value roughly a third of Alternative A. Tests of hydropower improvement flows, particularly during highly weighted summer months, reduce B2 relative to B1, while high fluctuation levels overall contribute to low FI values for B1 and B2. Steady, low weekend flows to promote benthic invertebrate production during May through August elevate the FI for D2 relative to D1, D3, and D4. The slightly higher FI values for long-term strategies E1 and E2 relative to E3–E6 can be attributed to the inclusion of both spring and fall HFEs in EI and E2. Water released for HFEs is not available for load following, thus reducing fluctuations and raising the FI. Likewise, E4, which includes fall but no spring HFEs, has a slightly elevated FI compared to E3, E5, and E6, which have no HFEs.

J.2.4 Time Off River

For rafting visitors, time off river to visit attractions and for other activities is important to the recreational experience (Stewart et al. 2000). Low river flows reduce travel speed for boats. Below a flow of about 10,000 cfs, there may be problems getting to camp on time and not enough time for stops at scheduled locations (Shelby et al. 1992).

J.2.4.1 Time Off River Index—Methods

The Time Off River Index (TORI) is computed using a daily flow factor (FF), which is an index from 0 to 1 that uses a flow threshold of 10,000 cfs. The daily FF is computed as follows, where the value within the brackets in the right column is assigned to the FF if the equation in the left column is satisfied, and where Q_{avg} is the average daily discharge:

$$FF_{Daily} = \left\{ \begin{array}{ll} \text{if } Q_{avg} \leq 10{,}000; & 0 \\ \text{if } 10{,}000 < Q_{avg} < 31{,}500; & 0.0000465 \times Q_{avg} - 0.465 \\ \text{if } Q_{avg} \geq 31{,}500; & 1 \end{array} \right\}$$

The annual TORI is the sum of the weighted seasonal index values. The seasonal index is the mean of the FF for all days within a given season, as above for NRI and FI:

$$TORI_{annual} = \{0.15\left(\frac{\sum_{winter} FF_{Daily}}{\sum Days_{winter}}\right) + 0.31\left(\frac{\sum_{spring/fall} FF_{Daily}}{\sum Days_{\frac{spring}{fall}}}\right) + 0.54\left(\frac{\sum_{\mathrm{summer}} \mathrm{FF_{daily}}}{\sum Days_{summer}}\right)\}$$

An overall annual mean index value for the 20-year modeling period was calculated as follows:

$$TORI = Average\ (TORI_{annual})_{2014-2033}$$

J.2.4.2 Time Off River Index—Results

Figure J-5 shows the TORI results for all long-term strategies. TORI values for all of the long-term strategies have similar mean and quartile values, due to similar average flows among the alternatives. The exception is the TORI for Alternative F, which is notably higher than for other alternatives. This difference is largely due to elevated flows during March–June under Alternative F, which falls within moderately to highly weighted seasons in the annual TORI computation. Figure J-6 shows elevated average daily discharge rates during March–June for Alternative F relative to the other alternatives. For all other long-term strategies, there would be negligible differences in time off river from current conditions.

J.2.5 Glen Canyon Rafting Use

Day-rafting trips in Glen Canyon are a popular visitor attraction of Glen Canyon National Recreation Area. These day-rafting trips regularly run as full-day, half-day, and rowed trips during March 1 to December 1. Glen Canyon rafting trips are not sensitive to flow levels (Bishop et al. 1987) and can generally operate during all releases up to powerplant capacity

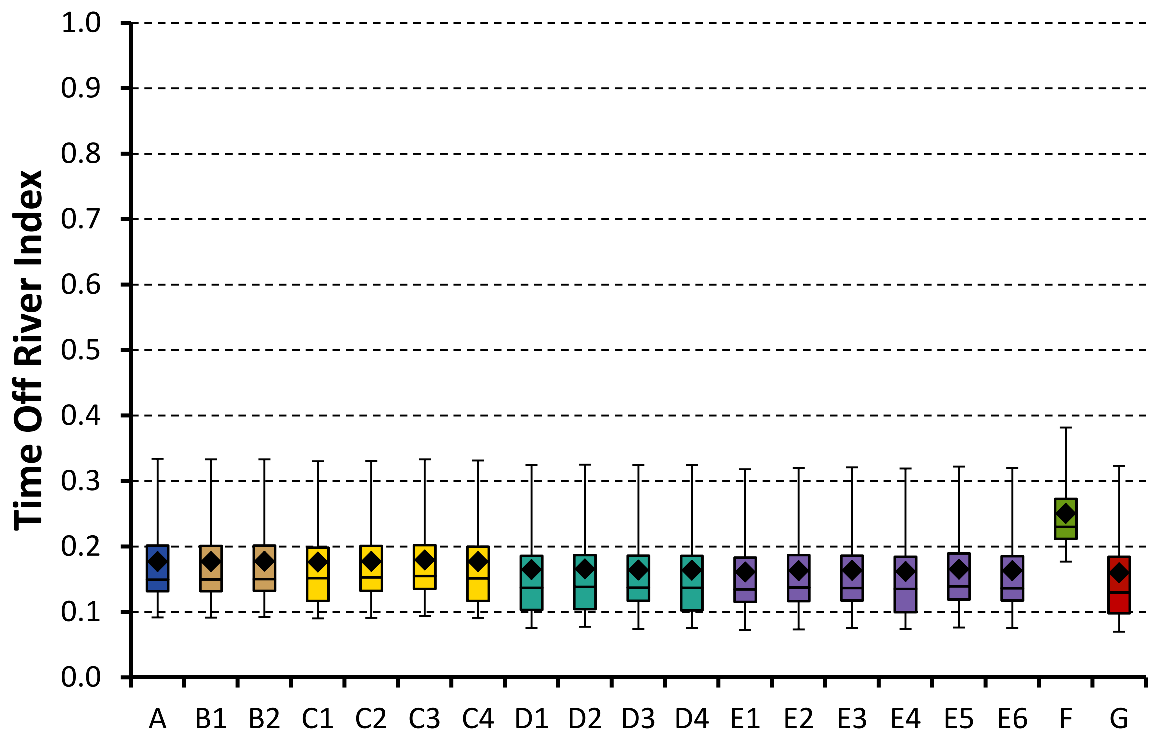

FIGURE J-5 Time Off River Index for LTEMP Long-Term Strategies (Increasing values indicate more time off river. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum.)

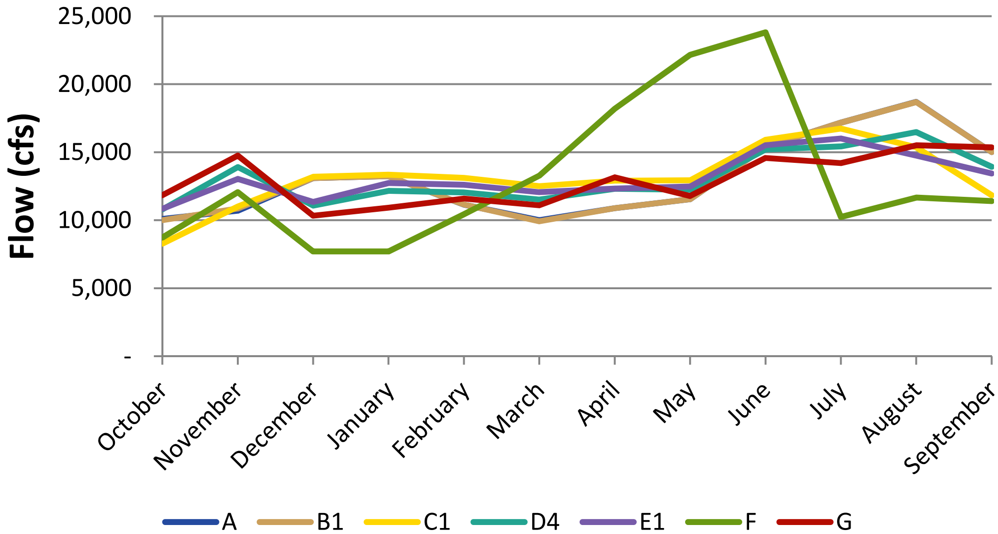

FIGURE J-6 Average Daily Discharge for All Modeled Traces and Years under LTEMP Alternatives

(31,500 cfs). However, when HFEs are run and the bypass tubes are activated, the turbulence at the loading dock is too great to safely load passengers and the commercial operator, Colorado River Discovery, ceases day-use rafting operations (Grim 2012).

J.2.5.1 Glen Canyon Rafting Use Metric—Methods

The Glen Canyon Rafting Use Metric (GCRM) represents the number of visitors unable to take day-rafting trips due to HFEs. Monthly passenger logs for Colorado River Discovery from 2011 to 2012 (Blais 2014) were used to estimate the number of daily passengers (*ADV*) for the months in which HFEs occur (March, April, May, October, and November). Data from 2013 was available but was not included because roadway closures that year potentially impacted visitor numbers. HFEs in spring and fall are possible each year. Estimates of the average daily rafting visitor count for lost trips from spring and fall HFEs are approximately 155 and 68, respectively. Thus, spring HFEs would have a much greater impact than fall HFEs due to higher rafting use in spring (more than double the passengers affected for a given HFE duration).

HFEs require day-raft concessioners to pull the boats from the water or relocate them. Therefore, the number of days lost for Glen Canyon rafting because of an HFE (D) is equal to the HFE duration plus 2 days prior and 2 days post HFE ($D = T_{HFE} + 4$ days) required to de-mobilize and re-mobilize rafting operations. The total number of lost rafting days (D) is multiplied by the estimated visitors per day (ADV) to calculate the number of passengers unable to raft due to an HFE. Note that, unlike the other recreation metrics in this appendix, the Glen Canyon Rafting Use Metric (GCRM) is a measure of an absolute effect, the actual number of annual lost visitor trips, as opposed to a relative index.

The operational 24-hr, 45,000 cfs spring high flow under Alternative F is taken into account in this analysis. No other high flows, such as equalization flows, except those distinctly defined as HFEs are considered. For each modeled year, there is the potential for a spring HFE, a fall HFE, or both to occur. The GCRM is calculated as follows for each HFE event.

$$GCRM_{HFE} = ADV\left[\frac{visitors}{day}\right] \times D\ [days]$$

If there are two HFEs within a single year, the number of passengers unable to raft is summed as in the following equation:

$$GCRM_{annual} = \sum\nolimits_{yearly} GCRM_{HFE}$$

The final metric value is the average number of passengers unable to raft the Glen Canyon reach for the 20-year LTEMP modeling period (2014 to 2033) due to HFEs:

$$GCRM = Average\ (GCRM_{annual})_{2014-2033}$$

J.2.5.2 Glen Canyon Rafting Use Metric—Results

Figure J-7 shows GCRM values for LTEMP alternatives and long-term strategies. As the metric is based on the number of HFEs, the GCRM closely resembles the pattern of HFEs under each alternative. This can be seen by comparing the GCRM values in Figure J-7 with the average HFE count in Figure J-8. Not shown for Alternative F is the annual 24-hr high flow that occurs in years without a spring HFE. This further contributes to increases the GCRM, resulting in the highest number of lost visitor trips for Alternative F. As spring trips have a higher number of passengers than fall trips, spring HFEs have a larger impact on lost visitor trips than do fall HFEs.

As they do not include HFEs, long-term strategies C3, E3, E5, and E6 incur no lost visitor rafting trips. With few HFEs and mostly fall HFEs, long-term strategies A and B1 and B2 have the next fewest lost trips on average, while C4 and E4 have only slightly more, due mainly to the absence of spring HFEs under these long-term strategies. E1 and E2 have more lost trips than E4 due to spring HFEs in the second 10 years of the LTEMP period that do not occur under E4. Long-term strategies C1–C2 and D1–D2 have similar numbers of lost visitor trips owing to similar numbers and durations of HFEs. Alternative G has the second highest number of lost trips at roughly 500 annually, due to a high number of HFEs, an estimated 24.5 over the 20-year LTEMP period, including HFEs of 96 hr or longer duration. Finally, Alternative F has the highest number of lost visitor trips, on average over 900 annually, due to the highest number of HFEs, an estimated 38.1 over the 20-year LTEMP period, including the annual 24-hr release in all summers of years without a spring HFE. In addition, roughly two-thirds of HFEs under Alternative F are of 96-hr duration, representing a large number of days closed to rafting.

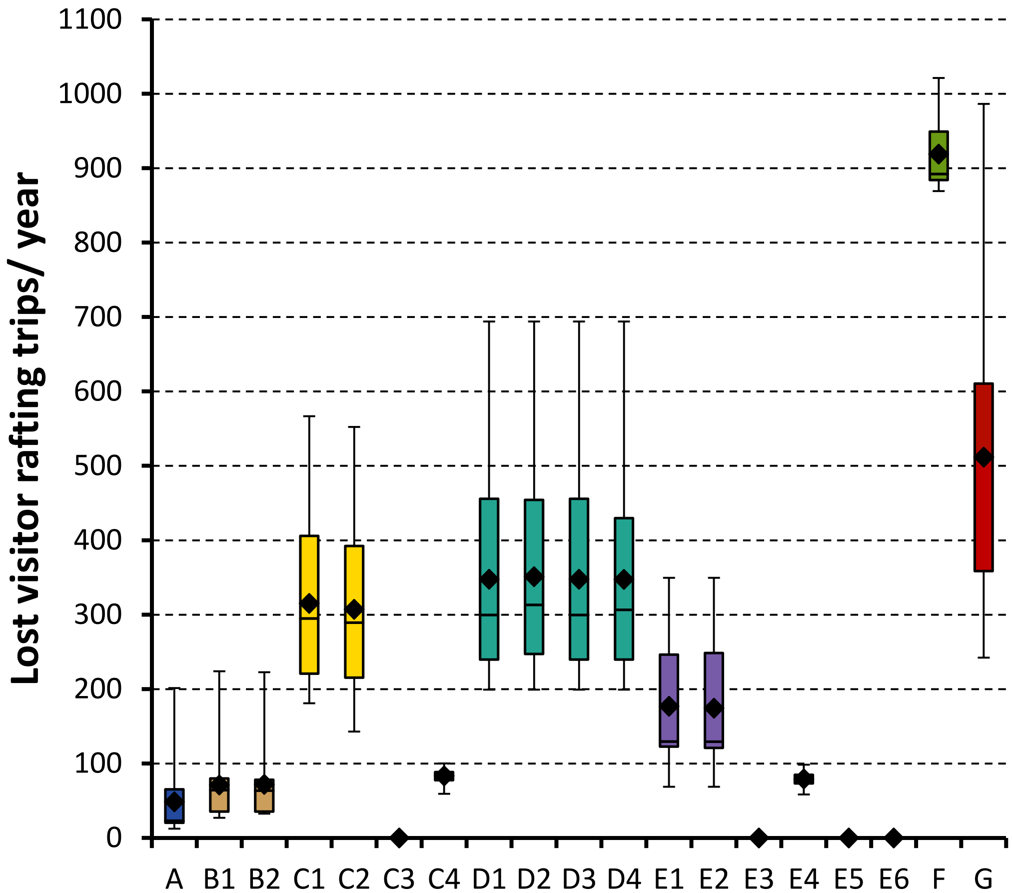

FIGURE J-7 Glen Canyon Rafting Metric for All LTEMP Long-Term Strategies (Values are estimated annual lost visitor rafting trips. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum.)

J.2.6 Glen Canyon Inundation Metric

The 15-mi stretch of Glen Canyon, from the Glen Canyon Dam to Lees Ferry, along the Colorado River is a hub for recreation within Glen Canyon National Recreation Area. Due to its unique geography, Lees Ferry is the only place directly accessible by car to visitors in hundreds of miles of canyon country. It is therefore an ideal location for boating, fishing, swimming, kayaking, camping, and hiking activities by visitors. However, these activities are directly downstream of the Glen Canyon Dam, and can be impacted by dam operation.

Surveys of users have indicated that the most ideal recreational conditions for Glen Canyon are flows from 8,000 to 20,000 cfs. Bishop et al. (1987) and Stewart et al. (2000) reported that anglers preferred a constant flow of about 10,000 cfs, while more recent information indicated Lees Ferry anglers preferred constant flows from 8,000 to 16,000 cfs

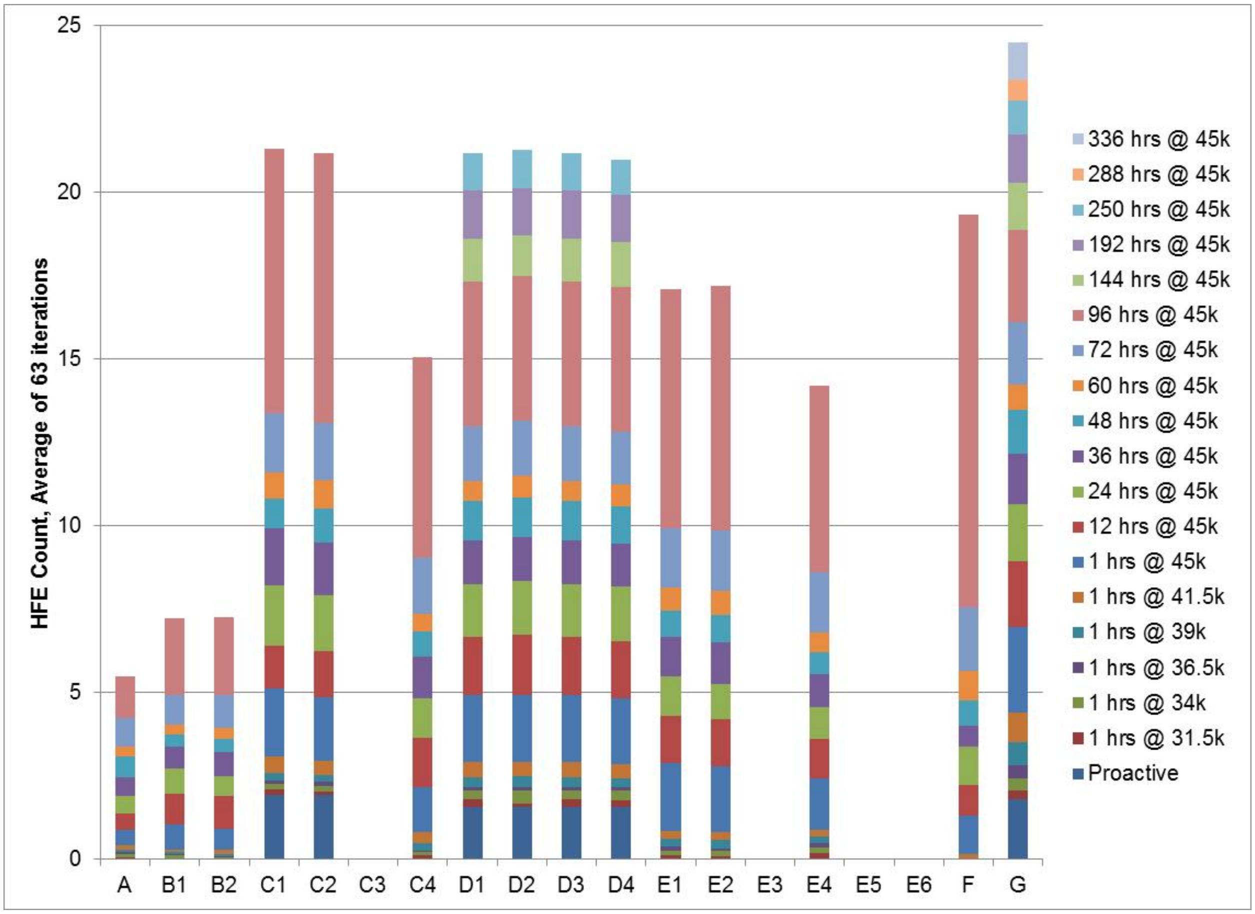

FIGURE J-8 Average Number of HFEs in the 20-Year LTEMP Period for LTEMP Long-Term Strategies

(Gunn 2012). Flows within the 8,000 to 20,000 cfs range are ideal for shoreline access for boaters, who primarily only report poor conditions or water level issues with extremely high or low flows. For example, the Colorado River Discovery day rafting service reported operating issues with flows below 3,000 cfs and inoperable conditions when bypass tubes are in operation (above 31,500 cfs), as they create too much turbulence below the dam (Grim 2012). Flows at or below 8,000 cfs may allow tamarisk tree growth and, as observed in the low summer flows of 2000 (Hjerpe and Kim 2001), may make prime angling spots impenetrable. At flows above 20,000 cfs, reduced participation in upstream fishing has been observed (McGinnis 2014).

J.2.6.1 Glen Canyon Inundation Metric—Methods

The Glen Canyon Inundation Metric (GCIM) represents the percentage of time that flow is at preferred levels for recreational experiences within the canyon, 8,000 to 20,000 cfs. Table J-2 presents a summary of recreational response to various discharge rates. This information was used in the computation of the Glen Canyon Inundation Metric as follows. A flow factor (FF) value from 0 to 1 is computed as a function of daily maximum discharge and

TABLE J-2 Recreation Response to Daily Maximum Flow

Flow (cfs)	Recreational Response
<3,000	Flows below 3,000 cfs are poor for boating and fishing.
3,000–8,000	Flows for fishing and boating get progressively better up to 8,000 cfs.
8,000–20,000	Flows are optimal for boating, fishing, and shoreline access.
20,000–31,500	Flows above 20,000 cfs get progressively worse for fishing and shoreline access.
>31,500	Flows above 31,500 cfs are poor for rafting, campable area, shoreline access, and fishing, and can adversely impact onshore recreational facilities.

the noted recreation responses, with higher values representing improved recreational experience. Daily FF values for discharges of 3,000 to 8,000 cfs and 20,000 to 31,500 cfs ranges were assigned values based on linear interpolation from 0 to 1 and 1 to 0, respectively. The daily FF is assigned as shown below, where the value in the right column within the brackets is assigned to FF if the equation in the left column is satisfied. Q_{max} refers to the daily maximum discharge released from the Glen Canyon Dam in cfs:

$$FF_{Daily} = \begin{cases} \text{if } Q_{max} \leq 3{,}000 \text{ cfs;} & 0 \\ \text{if } 3{,}000 < Q_{max} < 8{,}000\ cfs; & (Q_{max} \times 0.0002) - 0.60 \\ \text{if } 8{,}000 < Q_{max} < 20{,}000\ cfs & 1 \\ \text{if } 20{,}000 < Q_{max} < 31{,}500\ cfs; & 2.74 - (0.0000870 \times Q_{max}) \\ \text{if } Q_{max} \geq 31{,}500 \text{ cfs;} & 0 \end{cases}$$

An overall annual mean index value for the 20-year modeling period was computed for each alternative and used as the performance metric.

$$GCIM_{annual} = \{0.15\left(\frac{\sum_{winter} FF_{Daily}}{\sum Days_{winter}}\right) + 0.31\left(\frac{\sum_{spring/fall} FF_{Daily}}{\sum Days_{\frac{spring}{fall}}}\right) + 0.54\left(\frac{\sum_{\text{summer}} \text{FF}_{\text{daily}}}{\sum Days_{summer}}\right)\}$$

An overall annual mean index value for the 20-year modeling period was calculated as follows:

$$GCIM = Average\ (GCIM_{annual})_{2014-2033}$$

J.2.6.2 Glen Canyon Inundation Metric—Results

Results for the GCIM for LTEMP long-term strategies are shown in Figure J-9. Results are similar for all of the long-term strategies, except for Alternative F and, to a lesser extent, B2. Overall, index values are all high, above 0.9 for all but Alternative G, which has a mean value of about 0.85. Such high values indicate that discharge rates are in a range preferred for a variety of recreational activities most of the time under all alternatives and long-term strategies. The index value for Alternative F is reduced due to the large number of HFEs overall and to the high percentage of 96-hr HFEs, which together produce a relatively high number of days annually with flows above preferred levels. Similarly, high flows during hydropower improvement tests under B2 reduce its index value relative to B1 and most other long-term strategies. Other long-term strategies have values very close to that for Alternative A, with small deviations both higher and lower.

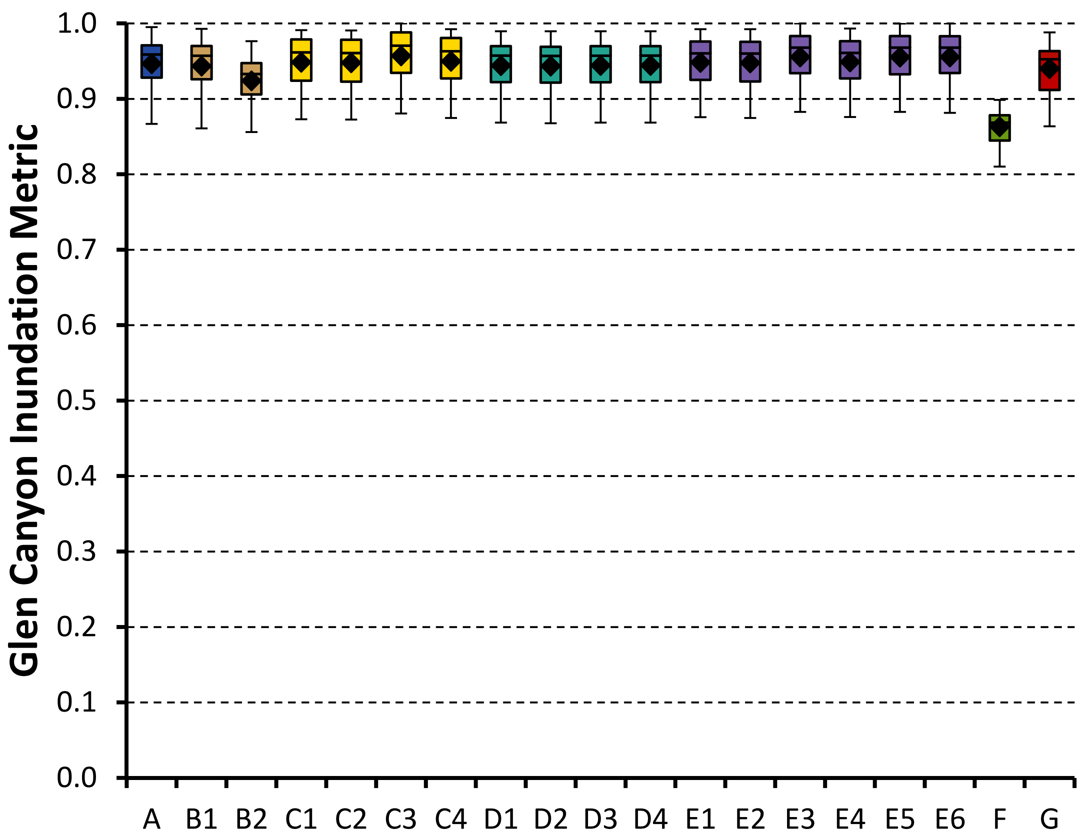

FIGURE J-9 Glen Canyon Inundation Metric for All LTEMP Long-Term Strategies (Increasing values indicate increasing frequency of flow levels preferred for recreation. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum.)

J.3 LAKE POWELL AND LAKE MEAD DOCK ACCESS

Lower-than-normal lake levels have been occurring in Lake Powell upstream of the Glen Canyon Dam and in Lake Mead, which lies at the end of the 277-mi stretch of the Colorado River through GCNP. At Lake Powell, low lake elevation has rendered some boat launch sites inaccessible, and, in October 2005, NPS completed a General Management Plan (GMP) Amendment for Low Water Conditions and Finding of No Significant Impact (NPS 2005), which identified a strategy for low-water operations. This amendment ensured the maintenance of the boat launch sites at Lake Mead despite low water levels by either extending or relocating existing launch ramps and marinas so as to be functional down to an elevation of 1,050 feet above mean sea level (AMSL). Similarly, at Lake Powell, a connection channel called Castle Rock Cut, located directly across from Wahweap Bay from the Stateline launch ramp, became inaccessible at lake levels below an elevation of 3,580 ft AMSL in 2014 (Elleard 2014).

Modeled end-of-month lake elevations from 63 historical traces were compared against these two elevations (1,050 ft AMSL for Lake Mead and 3,580 ft AMSL for Lake Powell) to determine the percentage of time that lake levels would potentially fall below these critical levels. The percentage of traces where monthly lake elevation fell below critical elevation for any month within a season over the 20-year LTEMP period for Lake Powell is shown in Figure J-10 for the recreational summer seasons of May, June, July, and August and in Figure J-11 for the recreational fall and spring months of March, April, September, and October. Figures J-12 and J-13 show the analogous percentages for Lake Mead. Note that since these figures were generated by recasting past hydrology, they show the potential future variability and range of lake elevation conditions relative to the access reference elevations, but they do not predict conditions for any particular future year or year-to-year trends. Thus, the year dates on the *x* axis have meaning only in the sense that they show a hypothetical future 20-year period.

These graphs show that monthly lake elevations fall on or below critical elevations during spring and summer months for roughly 22% of historical trace simulations for Lake Powell and roughly 25% of historical trace simulations for Lake Mead for all alternatives and long-term strategies over the LTEMP period. Table J-3 shows the percentages for all alternatives. While rates of access issues are substantial, the difference among alternatives is small, indicating overall impacts at the launch sites of Lake Mead or the Castle Rock Cut connection channel in Lake Powell are driven mainly by hydrology. At Lake Powell, on average over all seasons, all alternatives have slight increases in access impacts relative to Alternative A. Conversely, at Lake Mead, all alternatives exhibit slight decreases in access issues compared to Alternative A. It is not clearly the case, but this behavior might be the result of Alternative A having the lowest number of HFEs of all alternatives. Large volumes of water taken from Lake Powell for an HFE might temporarily drop the lake level below the access threshold when the lake level is near the threshold, while similarly reducing the frequency of access issues at Lake Mead, which receives an input pulse from an HFE.

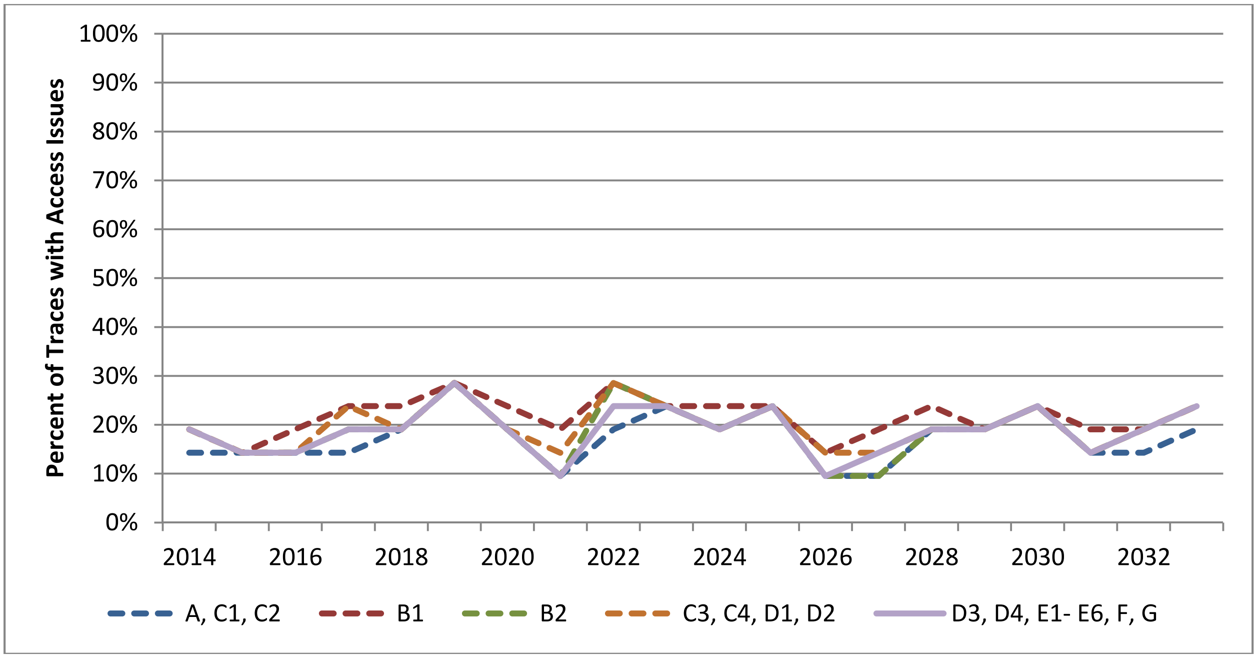

FIGURE J-10 Percentage of Traces Lake Powell Elevation Equal to or below 3,580 ft AMSL for the Summer Season

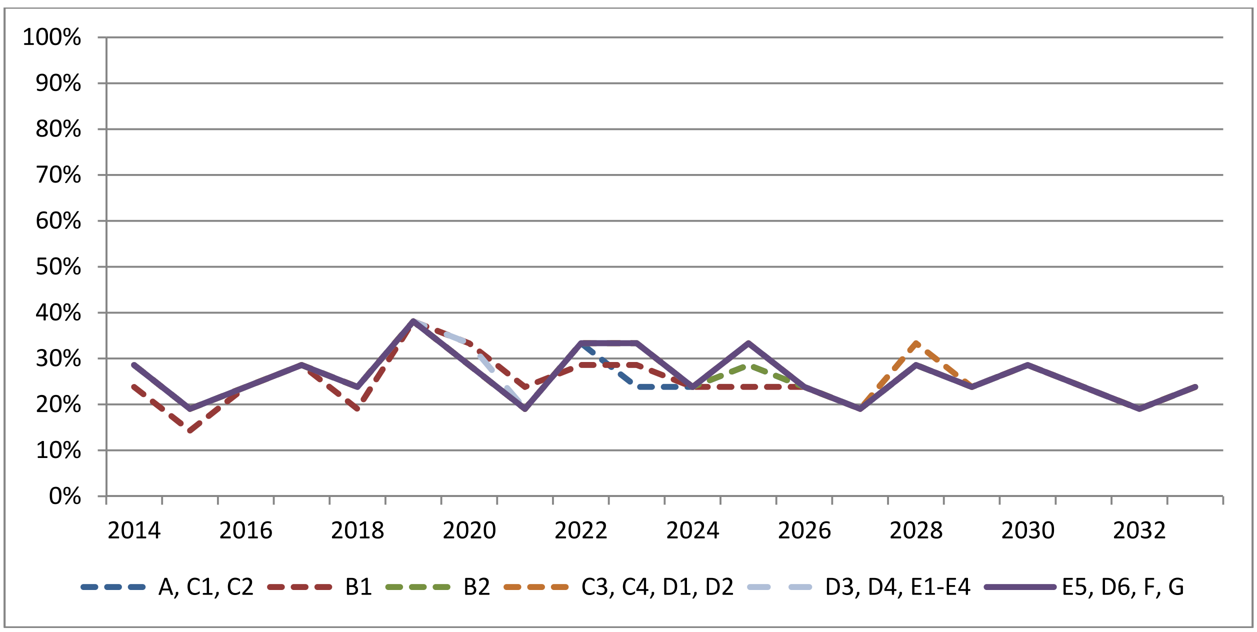

FIGURE J-11 Percentage of Traces Lake Powell Elevation Equal to or below 3,580 ft AMSL for the Fall and Spring Seasons

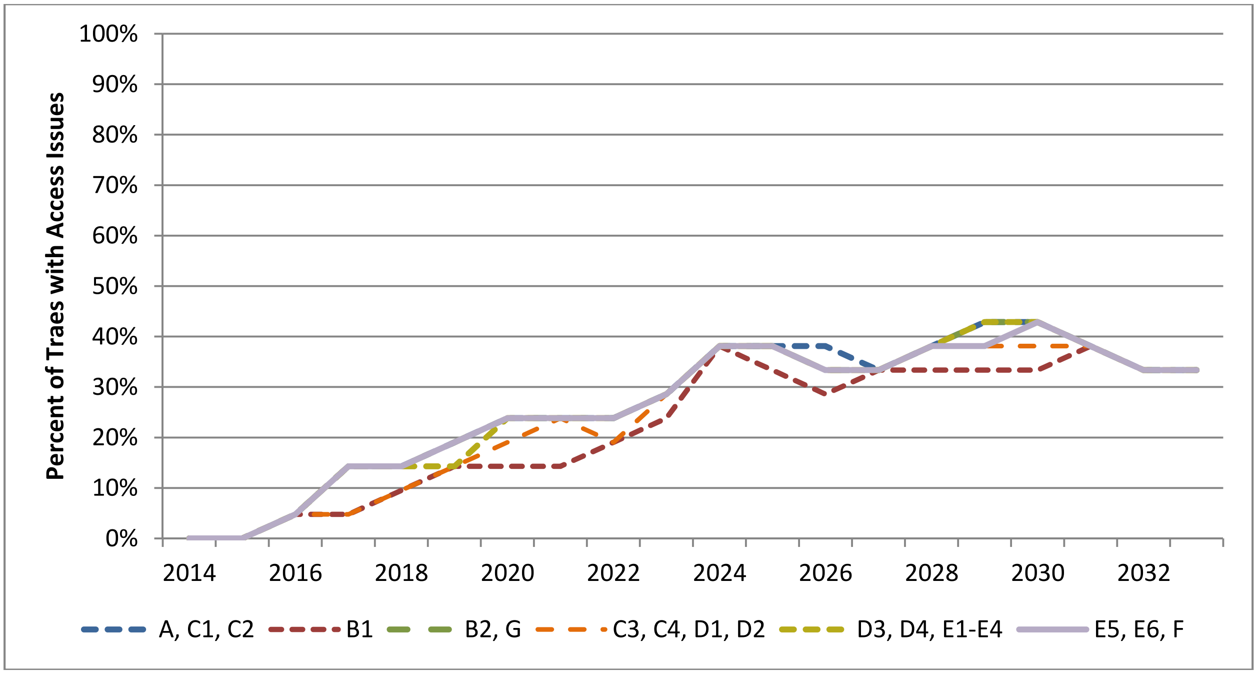

FIGURE J-12 Percentage of Traces Lake Mead Elevation Equal to or below 1,050 ft AMSL for the Summer Season

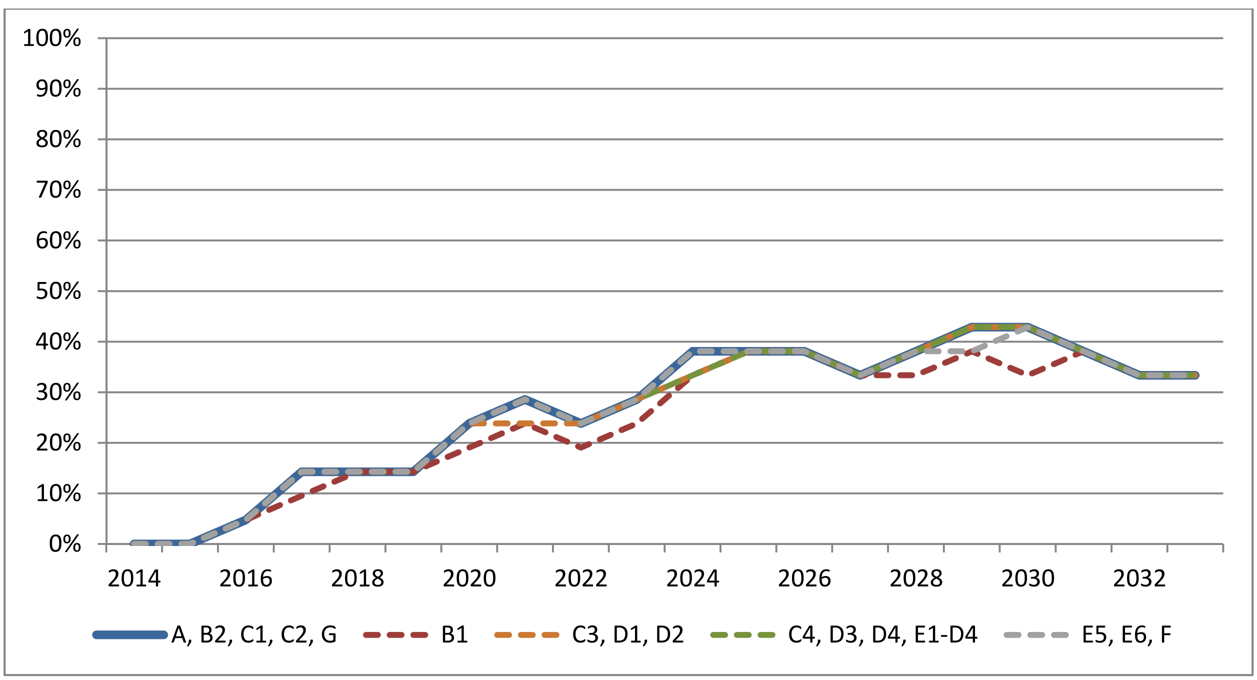

FIGURE J-13 Percentage of Traces Lake Mead Elevation Equal to or below 1,050 ft AMSL for the Fall and Spring Seasons

TABLE J-3 Summary of Recreation, Visitor Use, and Experience Metrics

Alternative/ Long-Term Strategy	CAI	NRI	FI	TORI	GCRM	GCIM	Lake Powell[a]	Lake Mead[a]
A	0.14	0.50	0.79	0.18	49	0.95	0%	0%
B1	0.15	0.39	0.42	0.18	71	0.94	2.5%	-10.6%
B2	0.12	0.26	0.26	0.18	72	0.92	4.4%	-3.5%
C1	0.38	0.75	0.93	0.18	315	0.95	0.37%	-0.31%
C2	0.37	0.73	0.93	0.18	307	0.95	0.37%	-0.31%
C3	0.04	0.76	0.92	0.18	0	0.96	5.5%	-4.4%
C4	0.33	0.76	0.93	0.18	83	0.95	5.5%	-4.1%
D1	0.36	0.45	0.74	0.16	347	0.94	4.7%	-3.5%
D2	0.36	0.60	0.78	0.16	351	0.94	5.5%	-4.1%
D3	0.36	0.45	0.72	0.16	347	0.94	5.1%	-2.5%
D4	0.36	0.45	0.74	0.16	347	0.94	5.1%	-2.5%
E1	0.30	0.37	0.57	0.16	177	0.95	5.1%	-1.3%
E2	0.29	0.30	0.53	0.16	174	0.95	5.1%	-2.5%
E3	0.03	0.32	0.52	0.16	0	0.96	5.1%	-1.3%
E4	0.27	0.29	0.53	0.16	79	0.95	5.1%	-1.3%
E5	0.03	0.33	0.52	0.17	0	0.96	4.7%	-2.5%
E6	0.03	0.32	0.52	0.16	0	0.96	4.7%	-2.5%
F	0.41	0.71	1.00	0.25	919	0.86	4.7%	-2.5%
G	0.45	0.96	0.98	0.16	512	0.94	4.7%	-1.9%

[a] Percentage difference from Alternative A in frequency of access issues; Alternative A has predicted access issues in 21.75% of future seasons for Lake Powell and 25.48% of future seasons for Lake Mead based on historical hydrology.

J.4 SUMMARY

Values for the means of the six metrics and frequency of Lake Powell and Lake Mead access issues discussed above are summarized in Table J-3. An index of 0 to 1 is used for CAI, NRI, FI, TORI, and GCIM, while GCRM is the estimated number of actual visitor trips lost due to HFEs. Access issues for Lake Powell and Lake Mead are the percent differences from Alternative A in the expected frequency of traces in which lake elevation falls below access thresholds in at least one month in either the spring–fall or summer seasons. The values shown in the table are mean values for 63 modeled hydrology–sediment conditions. Quartile values and minimum and maximum values for the six metrics can be seen in the respective box-and-whisker plots (Figures J-1 to J-9).

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